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VARIABILITY IN AIRCRAFT TURBINE ENGINE EMISSION MEASUREMENTS

Scott Research Laboratories,
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VARIABILITY IN AIRCRAFT TURBINE ENGINE EMISSION MEASUREMENTS

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Water Programs
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

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Using the special analysis system, the variability in the gas turbine emission measurements caused by the gas sample collection technique was studied using a Pratt and Whitney JT8D engine. An exhaust gas mixer and a detailed exhaust gas cross-section mapping technique were utilized for the verification of average exhaust emission concentrations.

The effects of approach to power setting and the effects of variations in fuel flow and thrust on the measurement of mass emission rates are discussed. The effects of ambient temperature and humidity on turbine engine emissions are examined.

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ABSTRACT

Under Environmental Protection Agency Contract Number 68-01-0443, Scott Research Laboratories, Inc., studied the causes of variability in turbine engine emission measurements. A state-of-the-art analysis system was built according to the specifications of the contract. The analysis system was evaluated for reliability in the handling and accuracy in the measurement of emissions.

Using the special analysis system, the variability in the gas turbine emission measurements caused by the gas sample collection technique was studied using a Pratt and Whitney JT8D engine. An exhaust gas mixer and a detailed exhaust gas cross-section mapping technique were utilized for the verification of average exhaust emission concentrations.

The effects of approach to power setting and the effects of variations in fuel flow and thrust on the measurement of mass emission rates are discussed. The effects of ambient temperature and humidity on turbine engine emissions are examined.

FORWARD

This report was prepared by Scott Research Laboratories, Inc., under Environmental Protection Agency Contract Number 68-01-0443. The work reported herein was adminstered under the direction of the Emission Control Technology Division, Office of Air and Water, Environmental Protection Agency with Dr. Robert E. Sampson serving as Project Officer. This report covers work performed from June 1972 through July 1973. The authors of this report are Anthony F. Souza and Louis R. Reckner.

The program described in this report was performed with the cooperation of the Federal Aviation Agency at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey, and we wish to acknowledge the special efforts of Mr. W. T. Westfield and Mr. G. Slusher of the F.A.A. The engine used on this program was supplied to the F.A.A. by Pratt and Whitney Aircraft.

1.0 INTRODUCTION

This report describes the work performed by Scott Research Laboratories, Inc. under Environmental Protection Agency Contract No. 68-01-0443. The major objective of the program was the determination of the causes of variability in the measurement of aircraft turbine engine emissions.

A state-of-the-art analysis system was designed and built according to the specifications of the contract. The analysis system was evaluated for reliability in the handling and accuracy in the measurement of emissions. Difficulties encountered are documented and changes or compromises required to produce a reliable system are discussed.

Using the special analysis system, the variability in gas turbine engine emission measurements caused by the exhaust sample collection technique was studied using a Pratt and Whitney JT8D gas turbine engine. An exhaust gas mixing technique and a detailed exhaust gas cross section mapping technique were utilized for the verification of average exhaust emission concentrations. The virtues of these techniques are discussed.

The variability in exhaust emission measurements produced by the direction of approach to a power setting and the effect of small variations in thrust and fuel flow on the measurement of mass emission rates are determined and compared to the actual run-to-run variations. All emission data collected are examined for the effect of ambient temperature and humidity on emissions from a gas turbine engine.

2.0 SAMPLING AND ANALYSIS SYSTEM

A complete sampling and analysis system was constructed according to the specifications in Attachment A-1 of the contract. This attachment is the test procedure published in the Federal Register of December 12, 1972 as the proposed aircraft turbine engine test procedure. Figure 2-1 illustrates the specified system. Figure 2-2 illustrates the details of the CO, CO_2, and NO_x leg of the system as built by Scott. Any deviations from Figure 2-1 are due to the requirements of the specific analyzers chosen or modifications necessary in the original design made to improve sample flow and sample integrity. The system features a heated sample train. All lines carrying exhaust sample are heated from the probe to the analyzers. The temperature of the sample gas is monitored at the analyzer exits in order to be certain that a heated sample is passing through the analyzers.

Previous emission sampling systems have used various techniques for the removal of water vapor from the exhaust sample. The water vapor, chiefly a product of combustion but also that present in the ambient air aspired by a fossil fueled engine, has been a problem both as optical interference to nondispersive infrared analyzers (NDIR), and as condensation in sample lines whose temperature is below the dew point of the moist exhaust gas sample. In previous exhaust analysis systems, the gas sample was dried by refrigeration of the sample gas to condense out water vapor. Non-afterburning gas turbine engines operate with considerable excess air. This yields an exhaust gas concentration of water vapor which can easily be held below saturation in moderately heated sample lines. At turbine exhaust water concentration levels, the water vapor interference to carbon monoxide NDIR analyzers can be controlled with optical filters. No refrigerators or drying columns are used in the present system. The sampling system delivers a hot moist sample to the analysers. All measurements are made "wet," that is, in concentrations based on actual values. In previous analysis systems where dryers were used, the "dry" concentrations measured had to be converted to "wet" values by calculating the proper dilution factor.

This sampling system makes use of a thermal converter in conjunction with a nitric oxide analyzer operating on the chemiluminescence principle. This replaces troublesome nondispersive ultraviolet analyzers for NO_2 and NDIR analyzers for NO which were previously used. The NO NDIR is quite

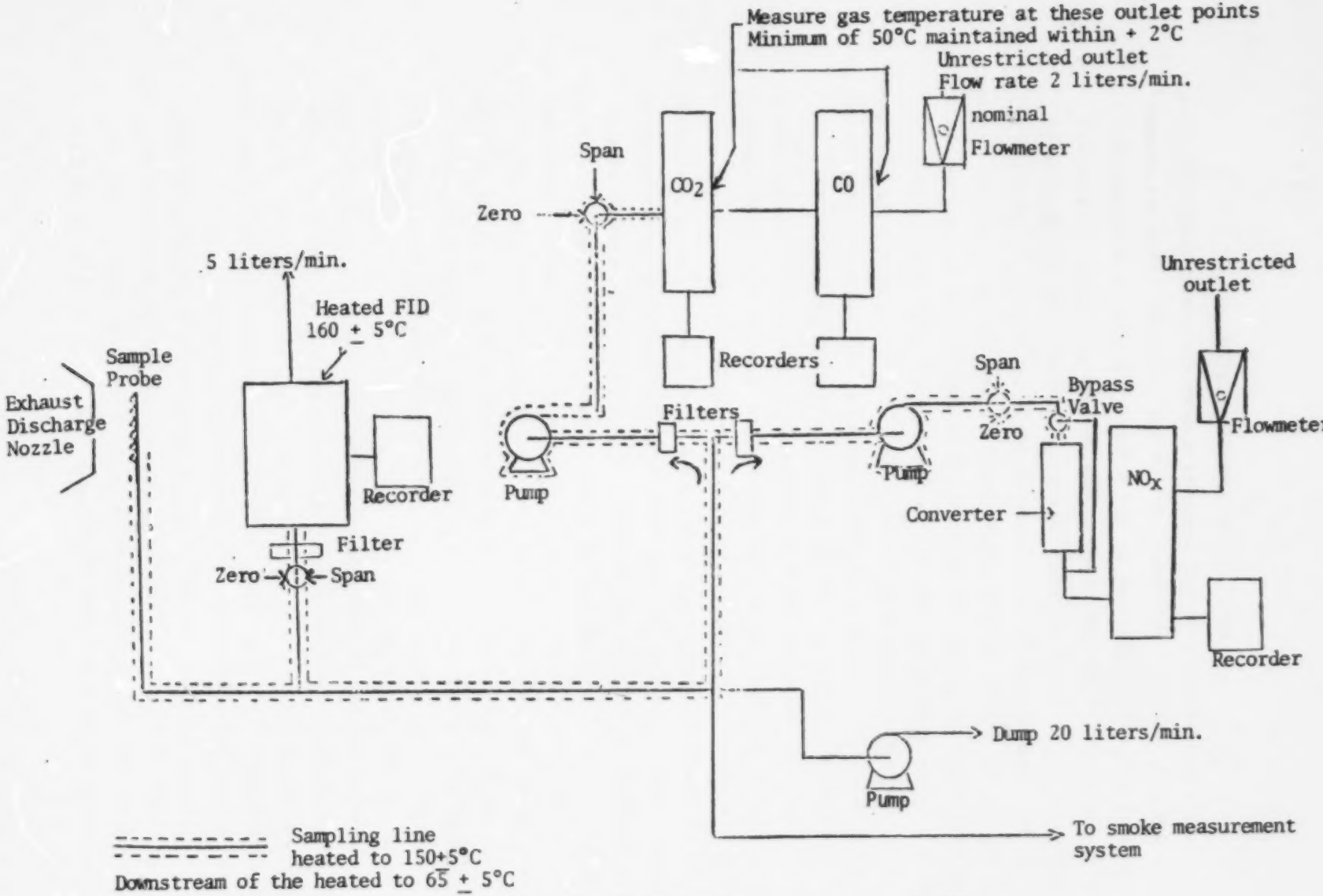
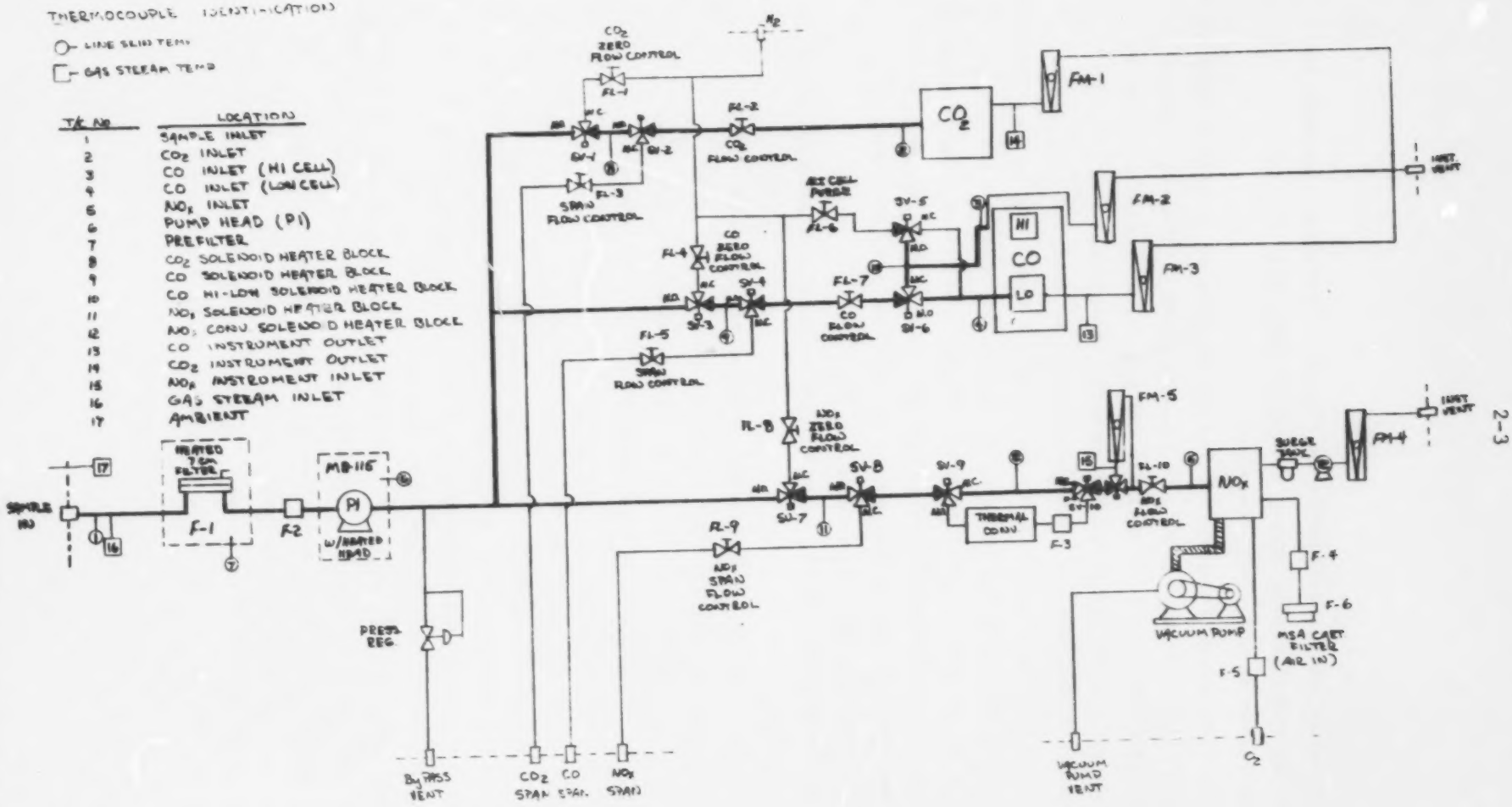


FIGURE 2-1 SAMPLING SYSTEM AND INSTRUMENT ARRANGEMENT



FLOW DIAGRAM - HEATED TURBINE EXHAUST ANALYSIS SYSTEM
1318-001

FIGURE 2-2

sensitive to water vapor and requires additional dehydration treatment in addition to the refrigeration drying technique acceptable for carbon monoxide and carbon dioxide NDIR analyzers

The flow schematic in Figure 2-2 can be seen to contain 3 separate legs with an analyzer in each leg: CO, CO_2 and NO-NO_x. The total hydrocarbon analyzer is mounted in a separate cabinet. The sample is driven by a single pump with an electrically heated head. Additional pumps in the heated hydrocarbon analyzer and chemiluminescence NO analyzer are used to bypass sample around those instruments where only a small sample flows through the detectors. Separate solenoid actuated valves are used in each leg to admit zero, span and sample gases to the analyzers. A heated sample line connects the heated hydrocarbon analyzer to the main heated sample line at a tee. Flowmeters are used at the outlet of each analyzer to permit the operator to set and maintain flow rates.

Departures and additions to the flow schematic of Attachment A-1 (Figure 2-1) are summarized below.

1. The CO and CO_2 analyzers were placed in parallel legs rather than series connected as specified to allow individual calibration.
2. One pump with a heated head was used to drive sample to the three analyzers in parallel legs making independent flow adjustments possible in each leg.
3. Three flowmeters were used instead of the two shown.
4. One heated prefilter was used to coincide with the single pump mentioned in 2 above.
5. Zero and span gases were admitted to the hydrocarbon analyzer just upstream of the detector. This is a built-in feature of the instrument selected for use on this program. Admission of the span gases directly to the detector provides speed of response which is desirable in routine testing programs. However, injection of zero and span gases at the probe end of the sample line offers a check on the system heated sample line and prefilter condition which is preferred. In the exhaust emission tests described later,

gases were admitted to the system inlet at the sample probe as a check on total system performance.

6. Flow control valves are used in each leg to adjust sample flow rates.
7. Flow control valves are used in each span and zero line to match flow of zero and span gases to the sample flow rates.
8. A bypass vent with a pressure regulator set at 5 psi was added downstream of the pump to act as a pressure relief. This protects the analyzers from high pressure surges.

In the system, sample lines are heated by passing an electric current through the stainless steel sample line tubing. The tubing is thermally insulated to decrease the electrical power required and to provide thermal stability. Electrical isolation from the analyzers was provided by short lengths of Teflon tubing at the necessary points. The solenoid valves which provide push button calibration were mounted on heated aluminum blocks. Also, the system pump in contact with sample gas had a heated head. Increased insulation around the solenoid valves and around the sample lines inside the NDIR analyzers was necessary to obtain a sample gas temperature of 50°C at the analyzer exits. A total of 17 thermocouples were used to insure that the sample line temperature was not excessively hot at any point.

Instruments selected for use in the system included Beckman Model 315 nondispersive infrared analyzers for carbon monoxide and carbon dioxide. The NO-NO_x analyzer is a Scott Model 125 chemiluminescence analyzer system which includes a thermal converter for NO_x. The total hydrocarbon analyzer is a Scott Model 215B heated hydrocarbon analyzer. It detects hydrocarbons by a flame ionization technique and incorporates a heated detector and pump assembly and a ten foot long heated sample line and heated prefilter assembly.

The heated hydrocarbon analyzer is sensitive to sample inlet pressure. It cannot draw a sample from a sample line whose internal pressure is below 750 mmHg. This translates in the case of a system configured like Figure 2-1 into a maximum line length from the probe to the heated hydrocarbon analyzer inlet of less than 40 feet and preferably less than 30 feet. For longer lines a pump must be added to the inlet line.

Eighty feet of heated 3/8-inch stainless steel sample line was fabricated. Flow tests indicated that the sample line could be easily resistance heated to 150°C using one 12.8 volt, 100 ampere transformer for each 40 foot segment. The sample line is connected as a load resistor across the secondary of the transformer and the primary voltage is controlled by an autotransformer. The sample lines are insulated with Fibrefax and encased in a vinyl zipper tube jacket.

3.0 SYSTEM EVALUATION

The system described in the previous section was thoroughly evaluated using both gas mixtures and turbine exhaust. The tests with gas mixtures were performed primarily in Scott's Plumsteadville laboratory while the tests utilizing turbine exhaust were conducted at the NAFEC facility near Pomona, New Jersey. This section deals specifically with the evaluation of the instrument system. The sampling system is discussed in Section 4.0.

The first step in system evaluation is a check for leaks in the system and the elimination of any that may be found. Since part of the system operates below ambient pressure, leaks will cause sample dilution and erroneous data. The leak test was performed by isolating the vacuum side of the system, evacuating this portion of the system with a vacuum pump, and monitoring on a vacuum gauge the time taken by the system to lose vacuum after the pump was shut off and a valve in the pump line closed. Points on the pressure side of the system were checked by pressurizing the system and checking for leaks at the joints with Snoop leak detector.

Next, a careful evaluation of each instrument and its sub-system was conducted in order to determine whether the specifications were met.

3.1 HYDROCARBON ANALYZER

The hydrocarbon concentration in turbine exhaust at some operating conditions is less than 0.3 ppm carbon. Therefore, it is necessary that the hydrocarbon analysis system have very low background. The zero gas specified in Attachment A-1 is air containing less than 2 ppm-C hydrocarbon. This is clearly inadequate for use in measuring turbine engine exhaust concentrations of 0.3 ppm-C. Air certified to contain less than 0.1 ppm-C was used as a hydrocarbon zero gas in these tests.

Since the hydrocarbon levels in gas turbine exhaust are very low, the sampling lines, prefilters, valves and other components in contact with the sample before it reaches the hydrocarbon detector must not remove hydrocarbons from the sampler or release incidental hydrocarbons. In a new system the hydrocarbons which are present after manufacture of the components must be driven off by operation of the system at elevated temperature for several hours. The background level is then checked periodically

by flowing hydrocarbon free air alternately directly into the analyzer and then through the complete sampling system. When the concentration measured reaches zero the sampling system is ready for operation.

Initially, the hydrocarbon analyzer was optimized for fuel and air flow rates and adjusted for minimum oxygen response. The oxygen response was less than 0.5%. Low oxygen response is not as important in non-afterburning turbine work as it is in diesel or automotive emission testing. Non-afterburning turbine engines operate with up to 200% excess air and the oxygen in the exhuast is never less than about 16%.

A comparison of instrument response to different classes of hydrocarbon was made using propylene, toluene and n-hexane standards containing approximately 35 ppm-C in nitrogen. The following table illustrates the relative response obtained with the three test gases. Also included is the response to the propane span gas and a second propane standard as a double check on the instrument span adjustment.

TABLE 3-1 RELATIVE RESPONSE OF HYDROCARBON INSTRUMENT TO SEVERAL HYDROCARBONS (BEFORE ADJUSTMENT)

Gas	Carbon No.	Cyl. Conc. ppm-C	FID Response ppm-C	Relative Response %
Propane in Air	3	147.3	147.3	100
Propane in N_2	3	15.24	15.04	98.7
Propylene	3	41.7	37.3	89.5
Toluene	7	31.1	28.2	90.7
n-Hexane	6	36.4	32.5	89.5

Average response to the three gases, propylene, toluene and n-hexane, was 89.9% and the maximum deviation from the average response was within 1.3%. Attachment A-1 specified that the response to the three gases should agree within 5%. This criterion was met. However, the response to these three gases was 10% less than the response to propane, indicating a problem of nonlinearity with carbon number. The instrument responded well to the two propane standards, one in air and the other in nitrogen, indicating very little oxygen response. The test specification is deficient in this respect since the hydrocarbon

instrument is spanned with propane and must respond linearly to the hydrocarbons of higher carbon number in gas turbine exhaust.

Further investigation revealed that a small adjustment in the air flow rate resolved this nonlinearity. Improvement was also noted in the oxygen effect and at less than 0.4%, it was well within the allowable limits. The following table illustrates the relative response obtained for the three classes of hydrocarbons tested with the new air flow rate. Also included are the two propane standards used to check the oxygen effect during this test.

TABLE 3-2 RELATIVE RESPONSE OF HYDROCARBON INSTRUMENT TO SEVERAL HYDROCARBONS (AFTER ADJUSTMENT)

Gas	Carbon No.	Cyl. Conc. ppm-C	FID Response ppm-C	Relative Response %
Propane in Air	3	8.82	8.82	100
Propane in N_2	3	15.24	15.18	99.6
Propylene	3	41 .7	41.4	99.2
Toluene	7	31.1	30.6	98.5
n-Hexane	6	36.4	35.9	98.7

The average response for the three gases was 98.8% and the maximum deviation of 0.4% was well within the 5% criteria set in Attachment A-1.

3.2 CARBON MONOXIDE AND CARBON DIOXIDE ANALYZERS

The specifications for the NDIR analyzers for carbon monoxide and carbon dioxide are as follows:

- Response time (electrical) - 90% of full scale in 0.5 seconds or less.
- Zero drift - less than ±1% of full scale in 2 hours on the most sensitve range.
- Span drift - less than ±1% of full scale in 2 hours on most sensitive range.
- Repeatability - ±1% of full scale.
- Noise - Less than 1% of full scale on most sensitive range.
- Cell temperature - minimum 50°C maintained within ±2°C.

Specified ranges and accuracies for the NDIR instruments are as follows for non-afterburning engines:

	Range	Accuracy
Carbon monoxide	0-100 ppm	±2% of full scale
	0-500 ppm	±1% of full scale
Carbon dioxide	0-2%	±1% of full scale
	0-5%	±1% of full scale

Of all these specifications the most difficult to meet was the zero drift limitation on the carbon monoxide analyzer. The carbon monoxide analyzer is a Beckman Model 315 Analyzer with 13¼ inch cells. In order to obtain low noise performance, a solid state chopper assembly was substituted for the original electromechanical assembly. Operation with less than ±1% of full scale zero drift was possible in the laboratory where operation of the instrument was on dry calibration gases and room air. In test cell operation with engine exhaust, the zero drift exceeded the specification. Zero drift appeared to be caused by both cyclic heating effects and soiling of the cell windows by fine particulate which had passed through the particulate filter. Coarse adjustments were made to the cell shutters to keep the analyzer and reference cells in balance until no further adjustment was possible. The cells were then removed and cleaned, restoring them to operation. The cells required cleaning after about 45 test runs. The cyclic drift was approximately ±1% of full scale. A modification has been developed recently at Scott to eliminate the cyclic drift. This eliminated any problem due to zero drift.

The extent of water vapor and carbon dioxide interference on the carbon monoxide analyzer was determined by passing a range of known concentrations of carbon dioxide and water vapor through the instrument and observing the response. Water vapor present in concentrations found in gas turbine exhaust can produce errors up to a few parts per million if not taken into consideration. Carbon dioxide interference is slightly less. Table 3-3 lists the corrections to be applied to the carbon monoxide readings obtained with the Scott analysis system.

TABLE 3-3 CORRECTIONS TO CO ANALYZER FOR WATER VAPOR AND CO_2 INTERFERENCE

Exhaust CO_2 Concentration (%)	CO Correction (ppm)	Exhaust Water Concentration (%)	CO Correction (ppm)
0.0	0.0	0.0	0.0
1.0	1.0	1.0	1.5
2.0	2.0	2.0	2.5
3.0	3.0	3.0	3.5
4.0	3.5	4.0	4.0
5.0	4.0	5.0	4.5
6.0	4.5	6.0	4.7
		7.0	5.0

3.3 NITROGEN OXIDES ANALYZER

No difficulty was experienced meeting the specification for the NO_x analyzer. The procedure to check the thermal converter can be improved by including the following points. Use an inert plastic bag such as Tedlar. Admit the NO in nitrogen to the bag first, the air second. Evacuate the bag before starting the test to remove leftover nitrogen dioxide. An electrical timer of the type in which a small electric motor drives a cam operated switch many be used to control two solenoid operated valves which switch the sample flow either through or bypassing the converter. The timer should be adjusted for one minute intervals. This device produces even intervals and frees the instrument operator for other duties while performing the converter check. A convenient daily check is one in which an NO_2 in air standard is passed through the converter. The resulting response should be consistent from day to day.

3.4 MEASUREMENT SYSTEM ERROR

The actual accuracy of error of a measuring system is a combination of the individual accuracies or errors of the parts of the system. In a typical NDIR system the major components which influence the accuracy are the instrument accuracy of the NDIR analyzer, span and zero gas accuracy,

and the analog recorder accuracy. The instrument accuracy is complicated by the addition of zero and span drift errors to the basic comparative accuracy or repeatability. A study was done on each of the analysis systems to predict the overall system accuracy. This study is presented in Appendix I.

3.5 CALIBRATION GAS ACCURACY

The magnitude of analysis errors resulting from inaccurately labeled calibration gases can be estimated for a cross section of laboratories by examining the data from Scott's Cross Reference Services. In these services, essentially identical cylinder mixtures are submitted to participating laboratories as unknowns every three months. The laboratories report their analyses to Scott, and the data are tabulated and analyzed. The two services which present mixtures typical of turbine exhaust are the diesel service and the nitric oxide service. A summary of the data for a recent group of cylinders is shown in Tables 3-4 and 3-5.

The standard deviation of the hydrocarbon data is seen to be nearly 50% of the mean value. However, by excluding four outlying observations the standard deviation is reduced to 15.5 or 5% of the mean. Similarly, the carbon monoxide and carbon dioxide data show standard deviations of 7% and 9% of the mean values, respectively. Removal of one outlier from each group reduces the deviations to 5% and 4%. Since all of the cylinders gave identical instrument responses before shipment to the participants, the data provides a good measure of error due to instrument calibration.

The nitric oxide data show standard deviations of approximately 13% of the mean value for both NDIR and chemiluminescence measurements. Removal of outliers still leaves the deviations at approximately 10%. Allowing for a 1 to 2% deviation in the nitric oxide cylinders, the deviations are still greater than for other components. The close agreement between nitric oxide data from the NDIR and CL analyses indicates that the errors are due to standards rather than instrument type. It must also be noted that while the participants in the cross reference services represent

TABLE 3-4 DIESEL CROSS REFERENCE SERVICE DATA

	Hydrocarbons as Methane (ppm) by FID	Carbon Monoxide (ppm) by NDIR	Carbon Dioxide (Vol. %) by NDIR
Average (no. data points)	323 (21)	498.5 (24)	3.44 (22)
Median	327	499.5	3.39
Range	15-875	400-545	3.1-4.66
Estimate of Standard Deviation	±150.73	±33.29	0.3

TABLE 3-5 NITRIC OXIDE CROSS REFERENCE SERVICE DATA

	Nitric Oxide (ppm) by NDIR	Nitric Oxide (ppm) by CL
Average (no. data points)	70.15 (28)	70.03 (23)
Median	69.00	68.00
Range	56-100	56-98
Estimate of Standard Deviation	±9.14	±9.09

a good sampling of laboratories in this country and abroad, they all participated in a similar cross check three months earlier. Thus, the data would be expected to show less deviation than if the laboratories had never participated in a cross reference program.

4.0 SAMPLE LINE EVALUATION

4.1 EFFECT OF SAMPLE LINE TEMPERATURE

The sample line must transport the exhaust from the probe to the instruments without affecting the concentration of any pollutant being measured. Sample lines up to 125 feet in length are in use at various turbine engine test stands in the country. Sample line temperatures can influence emission measurements in several ways. "Cold" sample lines can cause the water of combustion contained in the exhaust gas sample to condense. Liquid water absorbs nitrogen dioxide yielding a low reading for that constituent. "Cold" sample lines will also condense hydrocarbons with high boiling points. The hydrocarbon gases present in turbine exhaust are mostly cracked products at high power levels (high temperatures) but at the engine idle condition high boilers may be present which will condense in a "cold" line. The typical result when hydrocarbons deposit inside a sample line at idle, is that low readings are observed at idle. At high power settings where the hydrocarbon level is substantially lower, the hydrocarbon trace will slowly decrease, indicating that hydrocarbon deposited on the sample line wall is slowly evaporating into the sample stream. To prevent these problems, sample lines must be heated. The minimum temperature to prevent water condensation is 50°C. The minimum temperature to prevent hydrocarbon condensation is higher and becomes the minimum allowable temperature. From experience, this temperature is about 150°C.

The sampling line was evaluated both in the laboratory and in the test cell. The heated 3/8 inch stainless steel sample lines were tested in the laboratory in lengths up to 80 feet. Approximately 600 watts is required to maintain the sample line skin temperature at 150°C while flowing room air at 36 liters per minute. This flow rate is the flow required by the analysis system plus a bypass flow of 20 liters per minute. Laboratory evaluations were performed using propane in nitrogen standards as well as a jet fuel in nitrogen mixture. This mixture was obtained by adding a few drops of JP-5 fuel to a cylinder of dry nitrogen. The resulting gas had a measured hydrocarbon concentration of approximately 400 ppm-C. This mixture simulated the hydrocarbon emissions from a gas turbine engine at idle power setting.

No difference in reading was noted when propane was first admitted directly to the hydrocarbon analyzer and then passed through the 80 foot heated sample line. This was repeated over a range of sample line temperatures centered on 150°C. The JP-5 in nitrogen mixture, however, suffered losses in the sample line at all temperatures tried. The loss was minimum at 150°C sample line temperature. At sample line temperatures of 200°C and room temperature (25°C) approximately 15% of the hydrocarbons did not survive the 80 foot of sample line. Some losses also occured in the hydrocarbon analyzer prefilter where the concentration was reduced approximately 7% compared to direct injection into the hydrocarbon analyzer. When the sample line was reduced to 40 feet in length, the hydrocarbon losses were nearly the same as those experienced with the 80 foot line. It may be that the hydrocarbons were lost in the first few feet of sample line which was cooled by the gases being admitted from the relatively cool cylinder.

The test cell evaluations were performed using the configuration shown in Figure 4-1. In the test cell evaluations gas turbine exhaust was sampled using a system of four probes mounted inside a JT8D exhaust nozzle. The probe configurations are illustrated in Figure 4-2. This probe was designed by NAFEC personnel so that all sampling holes would be within the projection of the fan air/core air boundary. The probes consist of four closed end tubes with three sample inlet holes in each tube on circles concentric to the engine center line. The hole spacing on each probe is different. The probes are oriented along nozzle chord lines. The probes can be sampled individually or can be manifolded together through a system of solenoid operated valves.

The hydrocarbon loss tests were repeated using exhaust gases from a JT8D-11 engine. The results are shown in Table 4-1. No significant difference in hydrocarbon concentration was noted over sample line temperatures ranging from 150°F to 350°F, and sample line lengths from 20 to 80 feet.

4.2 EFFECT OF SAMPLE LINE LENGTH

The effect of sample line length was studied using a valving arrangement in which the sample line length could be changed from 80 feet to 40 feet total length. The sample line length between the heated hydrocarbon analyzer

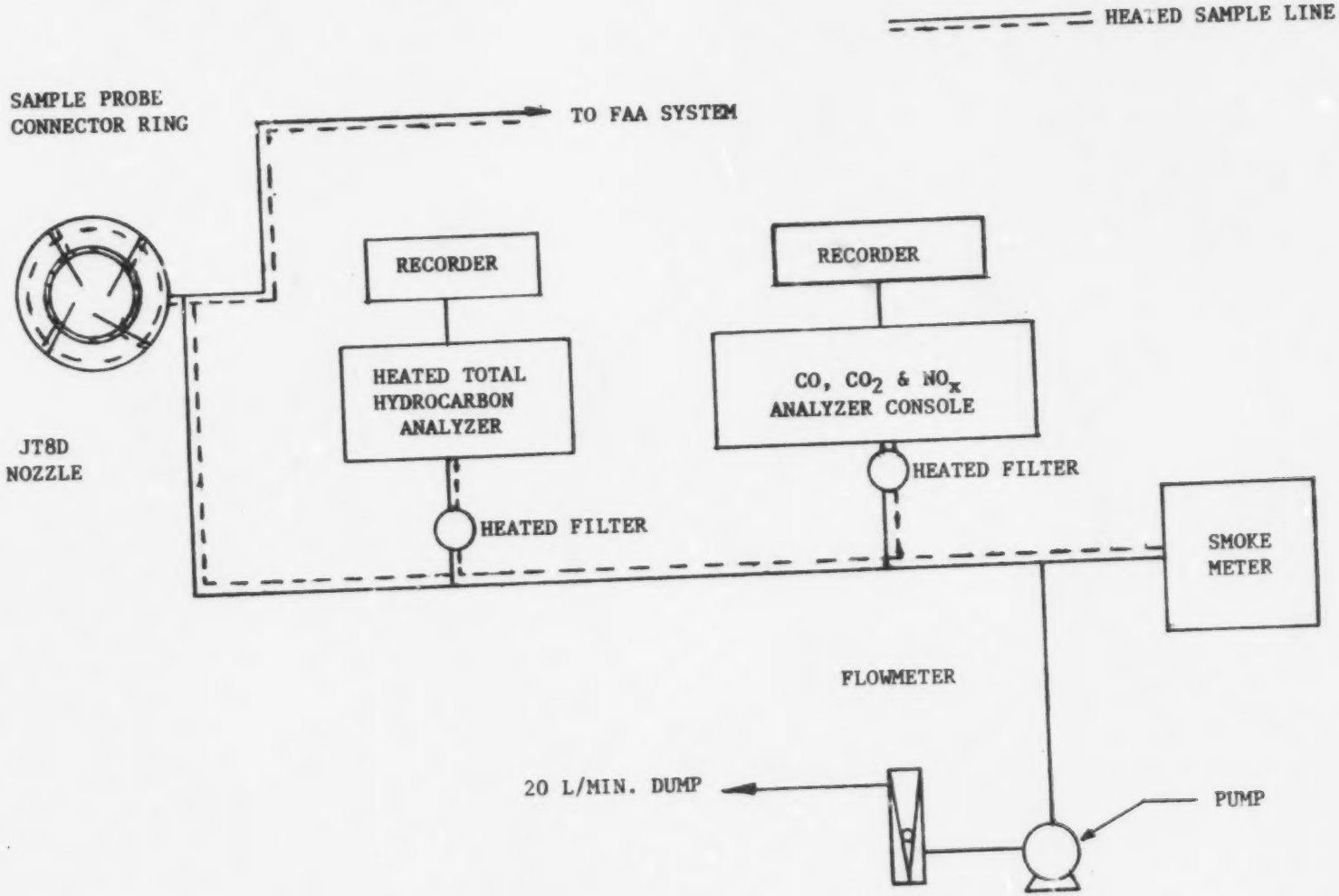


FIGURE 4-1 JT8D TURBINE SAMPLING SYSTEM

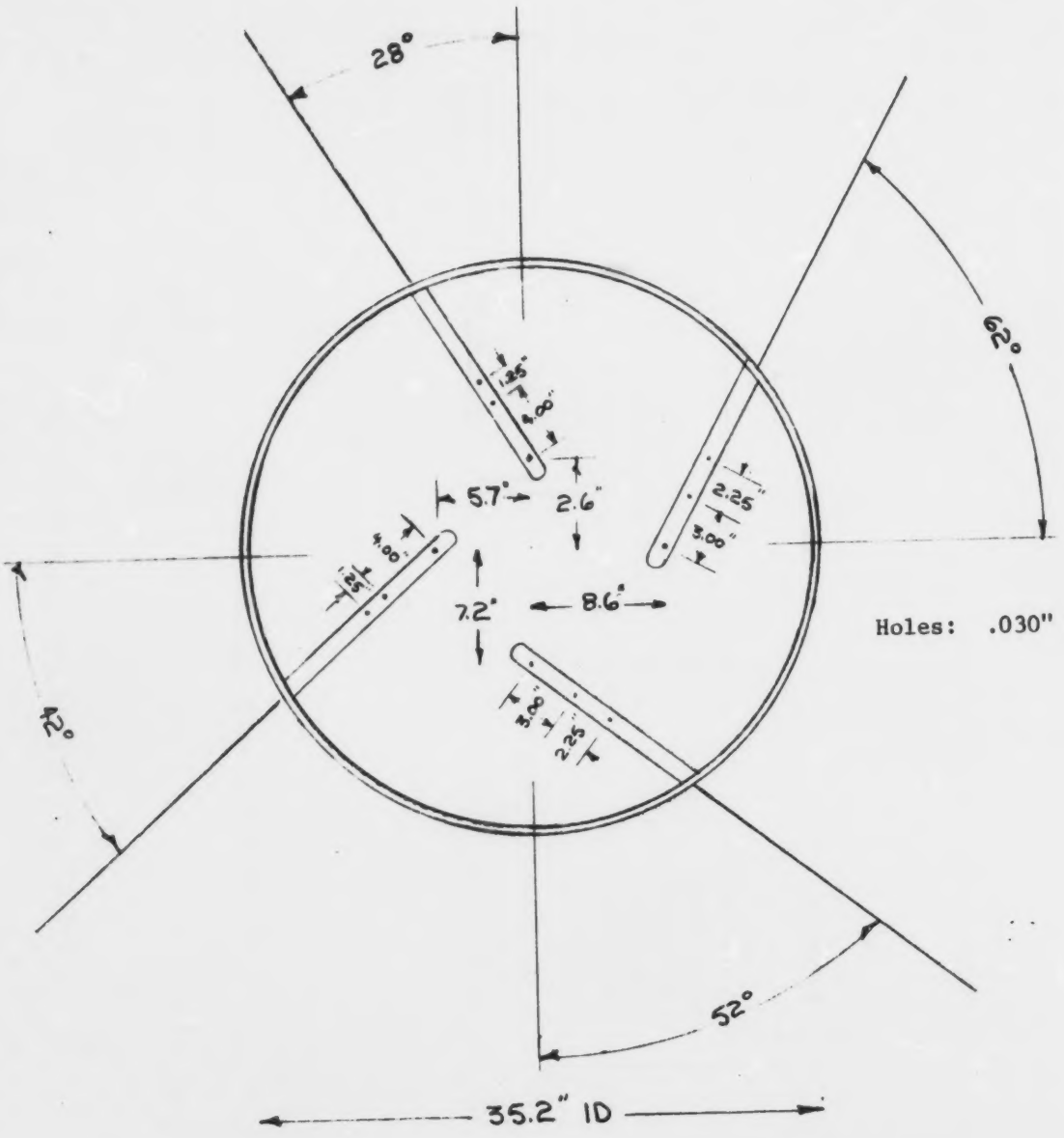


FIGURE 4-2 NAFEC PROBE AND HOLE PATTERN

TABLE 4-1 EFFECT OF SAMPLE LINE TEMPERATURE

JT8D-11 Emission Measurements Made With
Sample Line Bypass Flow Rate 20 l/m.

Tests made with up-stream sample pump.
Engine at Idle

Line Length (ft)	Line Temp. (^{o}F)	THC (ppm-C)	CO (ppm)	CO_2 (%)	NO_x (ppm)
80*	100	165.0	362	1.48	12.1
80	150	171.0	347	1.48	12.1
80	200	169.5	337	1.48	12.1
80	250	169.5	337	1.48	12.1
80	300	168.0	329	1.48	12.1
80	350	168.9	329	1.46	11.9
80	400	166.5	327	1.48	11.7
40**	100	172.5	340	1.48	12.1
40	150	172.5	362	1.48	12.1
40	200	171.0	355	1.48	12.1
40	250	171.0	347	1.48	12.1
40	300	171.0	362	1.48	12.1
40	350	171.0	355	1.48	12.1
40	400	171.0	370	1.46	12.1

* FID sample line - 60 ft.

** FID sample line - 20 ft.

and the remaining instruments was 20 feet. This meant that the sample line length from the probe to the hydrocarbon analyzer could be changed from 60 feet to 20 feet. In order to perform this test, a configuration change was made to the system. A pump was located just downstream of the probe so as to pressurize the sample line at engine idle and prevent problems with the hydrocarbon analyzer which will not operate properly with sample line pressures of less than 750 mmHg Abs. At engine power settings above idle, the pump is unnecessary and can be bypassed.

The results of these tests are shown in Table 4-2. No effect could be determined on the exhaust concentration measurements due to sample line length.

4.3 EFFECT OF SAMPLE FLOW RATE

The effect of sample flow rate was evaluated for lines of 20, 60 and 80 feet. Because the final 20 feet of sample line was between the hydrocarbon analyzer and the main gas analyzer cabinet, the actual sample line lengths from the exhaust sample probe to the hydrocarbon analyzer were 20 and 60 feet. The maximum flow rate allowable with the test system was determined by proper operation of the heated hydrocarbon detector which cannot operate with sample line pressure below 750 mmHg Abs. The maximum flow rate is also a function of sample line length since the pressure drop through a sample line increases with the length of the sample line. For short lines higher flow rates could be tolerated by the hydrocarbon detector.

With the engine at idle power setting, the maximum line length possible when using 20 liters per minute bypass flow was 20 feet from the sample probe to the hydrocarbon analyzer. At higher flow rates the sample line pressure was too low to allow normal hydrocarbon analyzer operation. A boost pump was added at the probe end of the sample line. It was a Teflon lined diaphragm type pump. Using this boost pump line lengths up to 80 feet were tested at bypass flow rates up to 40 liters per minute (53 liters per minute total flow).

No effect was noted on measured exhaust levels over a range of bypass rates from 10 to 40 liters per minute. Twenty liters per minute appears to be a reasonable operating point with line lengths up to 60 feet. With

TABLE 4-2 EFFECT OF SAMPLE LINE LENGTH

JT8D-11 Emission Measurements Made Through Heated Stainless Steel Sample Line at 150°C and Bypass Rate 20 l/min

Sample Line Length	THC (ppm-C)	CO (ppm)	CO_2 (%)	NO_x (ppm)
80	167	327	1.48	11.7
40	173	327	1.48	11.9
80	168	329	1.48	11.9
40	168	329	1.48	12.1

3/8" line lengths longer than 60 feet the maximum allowable transport time of two seconds becomes the governing criteria and bypass flow rates greater than 20 liters per minute are required.

Flow rate was varied from a maximum of 53 liters per minute total flow to minimum flow rate to satisfy the analyzers only, which was 13 liters per minute. Total flow rate was varied by changing the bypass flow rate. All tests were performed at engine idle condition. Table 4-3 presents some test results taken on two different days.

Hydrocarbon concentration remained unchanged with increasing flow rate, up until instrument performance was hampered by excessively low sample line pressure. The hydrocarbon response then decreased due to decreased sample pressure within the hydrocarbon detector.

4.4 EFFECT OF SAMPLE LINE MATERIAL

The effect of sample line material was evaluated by comparing two heated stainless steel lines, one of which was internally sleeved with Teflon tubing. These sample lines were operated over a range of flow rates and temperatures. Table 4-4 lists the results of these tests at different engine power settings. No significant differences could be detected between the measurements of hydrocarbons, carbon monoxide, carbon dioxide and nitrogen oxides made with the two lines. Calibration gas standards were passed through the two lines both before and after operation on gas turbine exhaust. No differences were noted between the instrument response to the gases passed through the lines and the response to the same gas injected directly into the instruments.

4.5 SMOKE SAMPLING

Exhaust gas was transported to the smoke meter through the stainless steel sample line during all tests where sampling was performed on gas turbine exhaust. Some difficulty was experienced on engine test runs 23 through 45 where the smoke numbers obtained did not correspond to those numbers obtained using a separate smoke sampling line. Dilution in the sample line was suspected, but the difficulty was traced to a problem

TABLE 4-3 EFFECT OF SAMPLE LINE FLOW RATE FOR DIFFERENT LENGTHS

JT8D-11 Emission Measurements Made Through Heated Stainless Steel Sample Line at 300°F

Engine at Idle

Bypass Flow Rate (l/min.)	THC (ppm-C)	CO (ppm)	CO_2 (%)	NO_x (ppm)
		40 Foot Length*		
10	171.0	362	1.46	12.5
20	172.5	370	1.46	12.5
30	170.1	375	1.46	12.5
40	169.5	370	1.46	12.5
		80 Foot Length**		
10	195.0	385	1.51	11.4
20	193.5	385	1.51	11.4
30	184.5	382	1.48	11.4
40	193.5	382	1.48	11.7

* Length from probe to hydrocarbon analyzer - 20 ft.

** Length from probe to hydrocarbon analyzer - 60 ft.

TABLE 4-4 EFFECT OF SAMPLE LINE MATERIAL

JT8D-11 Emission Measurements Made Through Heated Stainless Steel & Teflon Sample Lines

Read. No.	Power Condition	THC (ppm-C)		CO (ppm)		CO_2 (%)		NO_x (ppm)	
		Teflon	S. Steel	Teflon	S. Steel	Teflon	S. Steel	Teflon	S. Steel
24	Idle	141.0	144.0	336.0	336.0	1.48	1.48	13.0	13.2
27	Approach	8.4	7.2	64.7	64.7	1.75	1.79	38.2	38.2
38	Land	0.6	0.6	24.1	23.7	2.12	2.12	71.6	71.6
36	Cruise	0.3	0.3	16.2	15.7	2.25	2.30	92.2	92.2
33	Max. Cruise	0.3	0.3	11.0	10.9	2.53	2.60	121.2	123.4

within the smoke sampler itself. As a result of all the engine test runs to date, a light film of soot lines the sample line. This soot lining appeared to have no effect on the gas analysis being performed on the exhaust sample. However, later in the program, an apparent effect of soot lining was noted at low hydrocarbon concentrations during traverse testing. The smoke meter flow requirements and operation appeared not to be affected due to using the same sample lines as the gas analysis equipment. When no smoke samples were being taken using the gas sample line, a heated prefilter was added upstream of the sample line to keep particulate out of the line.

In general, separation of the smoke and gas sampling lines at the exit of the sampling probe is more convenient. This allows the use of a filter to prevent particulate from reaching the gas analyzers and minimum interaction in the flow requirements between the smoke and gas analysis systems.

5.0 CORRELATION OF EMISSION MEASUREMENT INSTRUMENTATION

The analysis system discussed in Sections 2, 3 and 4 was compared to an analysis system previously assembled by NAFEC. The NAFEC system consisted of Beckman NDIR analyzers for carbon dioxide and nitric oxide, a Beckman NDUV analyzer for nitrogen dioxide, a Beckman heated hydrocarbon detector, and an MSA NDIR for carbon monoxide. The system employed refrigeration drying of the sample before it was passed through the NDIR analyzers. The nitrogen dioxide and hydrocarbon measurements were made wet. Indicating Drierite was used as an additional drying agent upstream of the nitric oxide analyzer. The NAFEC exhaust analysis system was operated by NAFEC personnel in coincidence with the Scott system.

This provided two independent analyses of the same exhaust sample. The two systems were used to compare measurements made on the JT8D gas turbine engine exhaust emissions over a range of engine power settings.

Table 5-1 compares the data obtained during the first series of engine tests. There are obvious differences in the data for hydrocarbons and carbon monoxide. The exhaust analyses of hydrocarbons made by NAFEC were higher than Scott's analyses at all conditions and the difference increased with hydrocarbon level. An investigation showed that the differences between the systems were primarily caused by an inaccurately analyzed standard gas mixture. The NAFEC hydrocarbon standard marked 70 ppm propane contained only 50 ppm propane when analyzed against Scott standards. The NAFEC system could not measure less than 1 ppm-C. The Scott system was able to measure as low as 0.1 ppm-C. This still exceeded the low hydrocarbon levels emitted by the JT8D at maximum continuous power.

NAFEC measurements of carbon monoxide were either higher or lower than the Scott measurements depending on the concentration level. The NEFEC measurements were lower at high levels and higher at low levels. The disagreement was traced to a NAFEC standard labeled 71 ppm CO which was found to contain 83 ppm.

TABLE 5-1 JT8D TURBINE ENGINE EMISSIONS - WET

Read. No.	Power Cond.	EPR	THC(ppm-C)		CO(ppm)		CO_2(%)		NO_x(ppm)		NO_2(ppm)		NO(ppm)	
			Scott	FAA	Scott	FAA	Scott	FAA	Scott	FAA	Scott	FAA	Scott	FAA
2	Idle	1.042	130.0	180.0	334.0	327.0	1.52	1.60	13.3	11.8	-	7.0	-	4.8
4		1.042	97.8	140.0	284.0	282.0	1.49	1.58	13.6	15.3	8.2	8.0	5.4	7.3
5		1.076	35.4	62.0	160.0	163.0	1.59	1.65	18.3	21.2	7.9	10.0	10.4	11.2
8	App.	1.297	7.2	7.0	63.0	72.0	1.75	1.76	38.8	43.5	10.0	12.5	28.8	31.0
11	Cru.	1.671	<0.1	1.0	16.0	22.0	2.35	2.38	91.0	100.0	3.8	5.0	87.2	95.0
21	Max.	1.879	<0.1	0.0	13.2	15.9	2.50	2.59	121.4	135.8	3.6	5.0	117.8	130.8
22	T.O.	1.979	<0.1	-	7.1	11.8	2.70	2.75	145.0	162.8	2.0	5.0	143.0	157.8

The carbon dioxide concentration measurements agree within 1 to 6%. This spread, though more than desirable, is not surprising in light of the error analysis detailed in Appendix A-1 which predicts a system measurement error of 2.86% for carbon dioxide using NDIR. The carbon dioxide standards in use by NAFEC and Scott checked within 1.5% of each other.

The NAFEC nitric oxide analyses were consistently 10% higher than the Scott analyses. The span gases in use by the two measurement systems agreed within 2.5%. It is believed that the difference was due to the indicating Drierite used to dry the NAFEC sample. Nitric oxide analysis by NDIR using Drierite yields high results due to NO_2 conversion to NO by the cobalt chloride indicator. Non-indicating Drierite is preferred but is still known to give high readings. Since water interference to nitric oxide NDIR analyzers is severe, refrigeration drying and drying agents must be used to remove water vapor from the sample gas.

Agreement in the nitrogen dioxide measurements is poor. The concentration levels were always less than 15 ppm. The Scott measurements were obtained from the difference between the NO_x reading, obtained by passing the exhaust sample through the thermal converter which converts NO_2 to NO, and the NO reading which is obtained when the sample is admitted to the chemiluminescence analyzer directly. The subtraction of the two similar numbers (NO_x and NO) can lead to substantial error. Small errors in the NO_x and NO data result in large percentage differences in the NO_2 measurements. The NO_x differences ranged from 10 to 15% with the NAFEC readings higher than the Scott readings. Since NO_x present in the gas turbine exhaust is mostly NO, the errors present in the NO measurement controled the error in the NO_x measurement.

A cylinder containing reference standards of propane and carbon monoxide in nitrogen was provided by the EPA project monitor. This referee gas standard was used to reference both measuring systems to the Environmental Protection Agency laboratories and to each other. The referee standard confirmed that the analyses of the NAFEC hydrocarbon and carbon monoxide calibration gases were in error.

6.0 EVALUATION OF SAMPLING METHODS

The effect of the exhaust sample collection procedure on the accuracy of the exhaust emission measurement was evaluated. The composition of exhaust gas sample must be an accurate representation of the turbine exhaust stream. The exhaust stream of a mixed-flow turbine engine, such as the JT8D, has a complex non-uniform gas concentration distribution.

The pattern of exhaust gases consists of the core engine flow which occupies the central portion of the exhaust plume and the fan air which has bypassed the combustion process and occupies an imaginary concentric outer cylinder. Within the core engine exhaust region the distribution of exhaust gas concentrations is further influenced by the distribution of combustion chambers, turbine blades and flow straightening vanes, and by other aerodynamic influences. A sampling probe which is to deliver a representative exhaust gas sample to the analyzers must coordinate the various regions of the exhaust by a judicious location of sample inlet ports.

In order to evaluate the sampling accuracy and representativeness of sampling probe design, it is first necessary to know the true average concentration present in the exhaust stream. The first attempt at measuring this true engine exhaust emission level used a mixer located behind the gas turbine engine. It was hoped that this mixer would mix the exhaust gases into a homogeneous product such that the gas concentrations would be the same at any point in the mixer exhaust stream. Due to difficulties encountered with this technique a second technique was evaluated wherein measurements were made point by point across the gas turbine engine exhaust plume.

6.1 DESIGN AND TESTING OF MIXING CHAMBER

A mixer which would swirl the exhaust and produce a uniform mixture through turbulence was considered first. It soon became apparent that tolerable pressure drops were not attainable with this type of mixer.

6.1.1 Kenics Mixer

Specifications were given to the Kenics Corporation to enable them to finalize the design and quotation of a mixer to completely mix the exhaust emissions from a JT8D gas turbine engine. The full power exhaust flow, temperature and pressure were used as the design points. A pressure drop through the mixer of less than 1.8 pounds per square inch was specified as being acceptable. This value was arrived at from conversations with Pratt and Whitney aircraft engineers and the EPA project officer. Although the effect of back pressure on the engine was unknown, this value represented a low value which was initially considered attainable by Kenics. In the final analysis, however, the pressure drop calculated by Kenics could not be obtained in a 36 inch diameter, 3 element mixer. A 48 inch diameter, 2 element mixer was quoted which would have a pressure drop of 2.9 psi.

The exhaust gas parameters used by Kenics to calculate the expected pressure drop included a value of 29.5 psia gas pressure. This is the turbine discharge pressure in a normal engine. The actual pressure in the mixer would be a decreasing amount, decreasing from 29.5 psia to 14.7 psia, the ambient value. Using the value of 14.7 psia in the Kenics calculation of mixer pressure drop, yields a pressure drop of approximately 6 psig or twice that calculated by Kenics for the 48 inch mixer. These values of pressure drop were believed to be too high to allow normal operation of the JT8D. Although some emission data may have been obtained at low power settings, it did not seem to be worth the time and expenditure involved.

6.1.2 Straight Pipe Mixer

The EPA project officer agreed with Scott's recommendation to abandon the Kenics mixer and to proceed with a straight pipe mixer 36 inches in diameter. The pipe was made up of a 5 foot adapter section to fasten onto the jet engine followed by a 6 inch long section which housed experimental probes and three 20 foot sections providing a total mixing tube length of over 60 feet. Suitable pipe stands were fabricated to hold the mixer in place and a 1/8" thick silicone rubber sheet was used as a flexible coupling between the adapter section and the engine exhaust nozzle. This flexible pressure seal was held in place by three steel hoops 1/16" thick, fastened together at the ends by a 3/8" bolt.

Preliminary runs were made with the first 5-foot adapter section attached to the nozzle. This section increased the effective nozzle length by 15 inches. The engine was operated at idle, high idle, and approach power in this configuration. At approach power the engine vibration limit was exceeded, so no higher power settings were attempted. Examination of the engine operating data revealed that the engine was operating off its design operating line. Concern was caused by the fact that the N_1 and N_2 rotor speeds were diverging. The next step was to check the engine operation with the first 20-foot section added to the existing 5-foot adapter. In this configuration the engine was run at idle and high idle. The results were the same as with the 5-foot adapter. Consultations with the engine manufacturer resulted in a decision to discontinue operation with the mixer attached.

6.2 TRAVERSING PROBE

Pratt and Whitney Aircraft Corp. reported that the total pressure profile across the JT8D exhaust was flat within 4% at idle and at maximum continuous power it was essentially flat with one pocket which deviated by 6%. If the density is also flat, an area weighted average concentration should produce a result which is representative of actual emission rates.

A traversing probe was fabricated and placed so that the probe inlet was located two inches behind the nozzle exhaust plane. An array of 177 sample points were laid out.

6.2.1 Design and Operation of Traversing Probe

The traversing probe designed and constructed by Scott for use on this program can position a probe anywhere in a vertical plane measuring 39 inches wide and 34 inches high. It was mounted on a welded frame so that the center of the traverse area coincided with the center of the JT8D engine mounted on the NAFEC test stand. Figure 6-1 illustrates the traversing probe.

The probe was positioned by electric motor driven ball screw jacks which moved the probe in both the horizontal and vertical directions.

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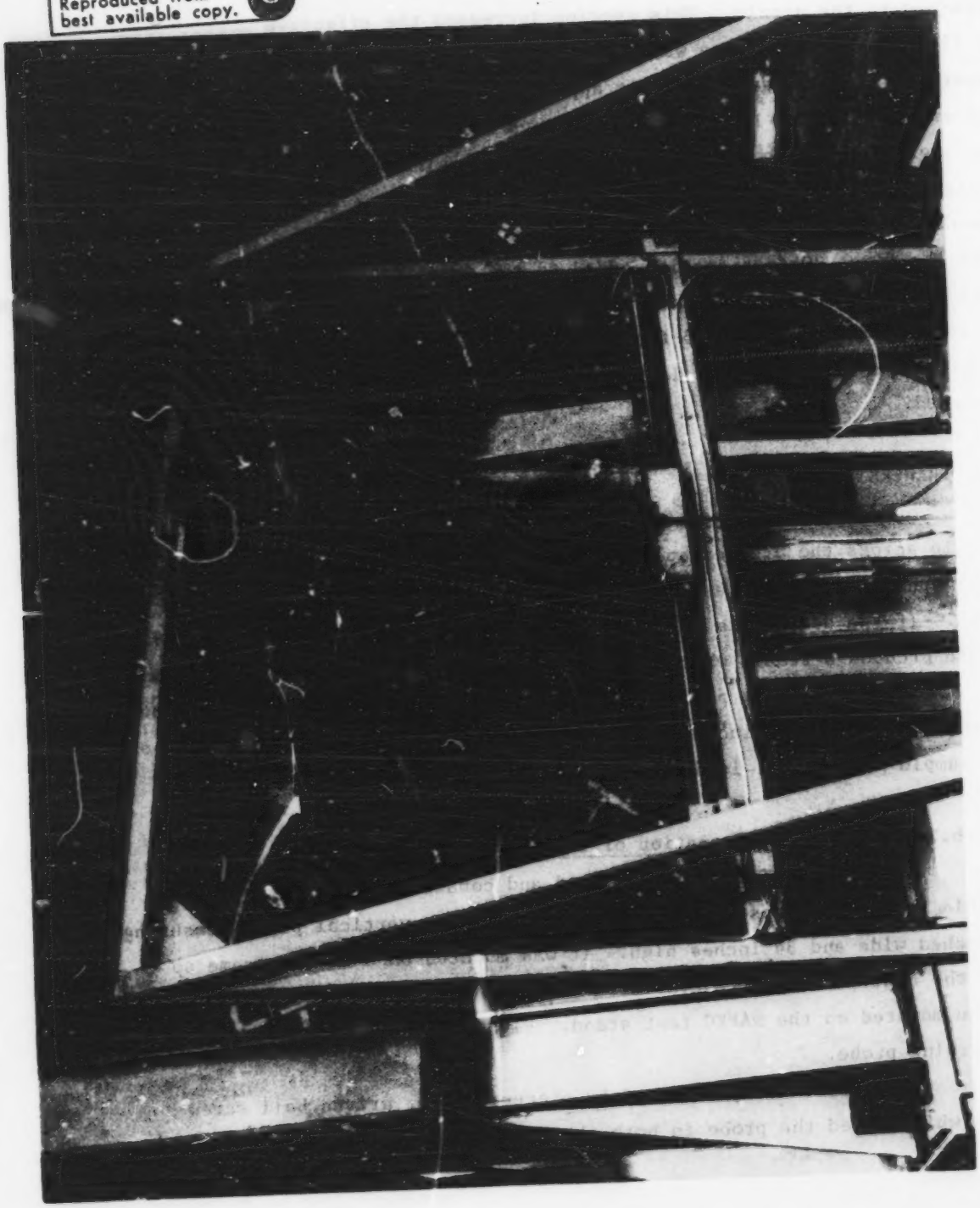

FIGURE 6-1 TRAVERSING PROBE

The probe carriage rode on two horizontal steel rods using Thompson linear ball bushings. The horizontal carriage supported the bottom end of two vertical rods which guided the vertical probe carriage. The top end of the rods rode along a horizontal track. The exhaust sampling probe was fastened to the vertical carriage and was thus capable of being moved both horizontally and vertically.

Probe position was monitored with a digital voltmeter connected to a potentiometer voltage divider. The potentiometer was a ten-turn device gear driven by the electric motor actuators. The system was calibrated so that a one millivolt signal equaled 0.1 inches. The probe position was repeatable and known within one tenth of an inch. Operation was smooth and controlled. Variable speed motor control enabled fast traversing or slow approach to a precise position. No problems were experienced with the traversing probe except for the loosening of a few screws due to the severe environment. The probe worked well at all power settings including take-off power.

The sampling probe which was used to make detailed measurements of the jet engine exhaust plane is shown in Figure 6-2. The inlet to the probe is a 1/4 inch diameter stainless steel tube.

6.2.2 Nozzle Traverse Data

Detailed traverse data were obtained on the JT8D engine at four power settings: Idle, holding, approach and maximum continuous power. Some cursory traverses were also made at take-off power. Take-off power may only be maintained for five minute periods. It must be followed by sufficient time at reduced power after the take-off run so as to allow the engine to cool down to operating temperature.

The array was a rectangular grid circumscribed by the exhaust nozzle diameter. The sample points were located two inches apart. The concentration averages were calculated at the center of two inch squares except for those sample points in the outer periphery. These areas were assumed to be combinations of triangles, rectangles and sections of a circle with the sample point concentrations assumed to be representative of the whole area. The products of the concentration x area for each section were summed and divided by the total area to obtain the area weighted average.

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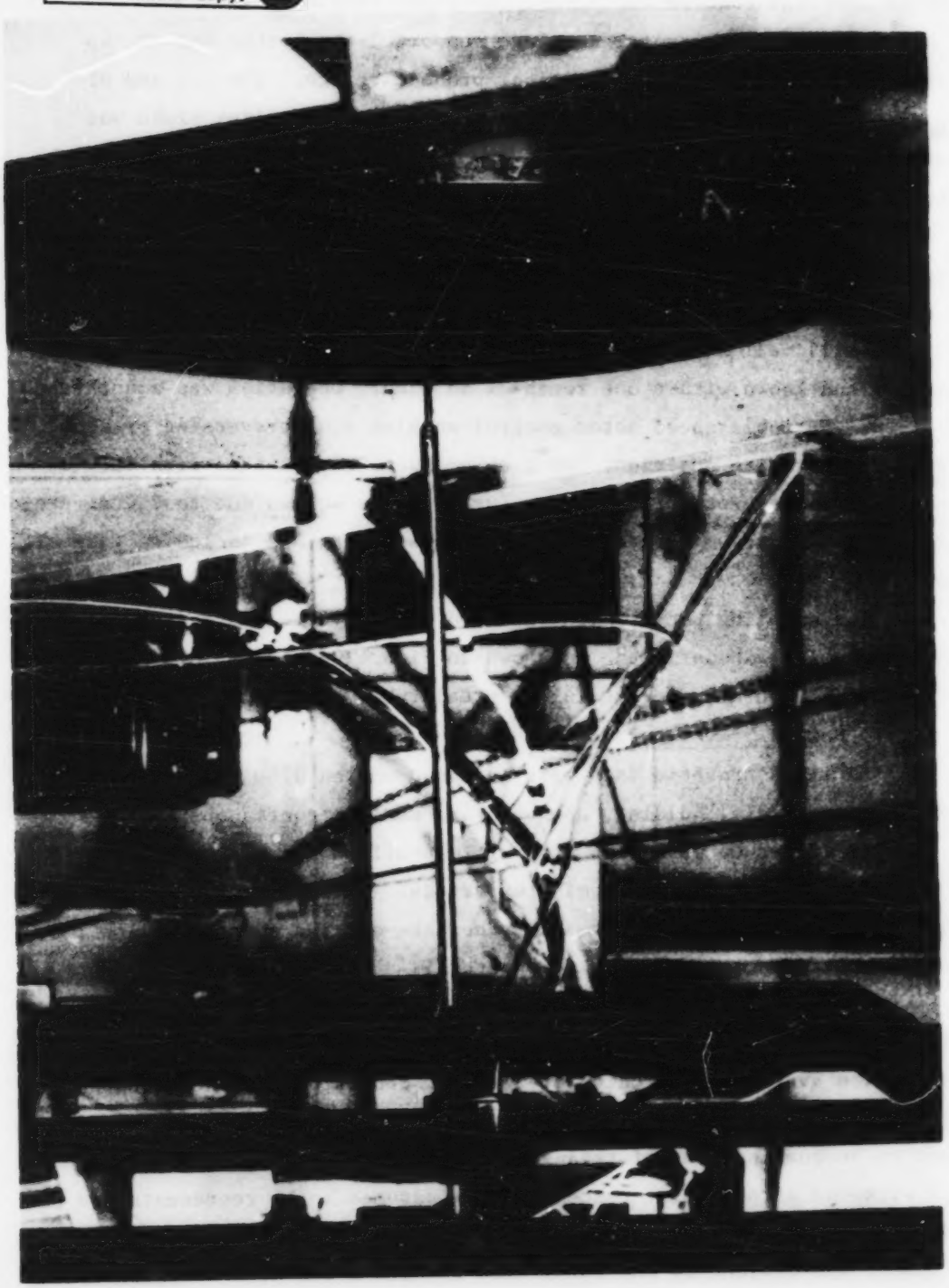


FIGURE 6-2 SAMPLING PROBE

Maps of exhaust plane gas concentrations were constructed using the traverse data. Concentration maps for carbon monoxide, carbon dioxide, total hydrocarbons and nitrogen oxides were drawn for each of the four power settings tested. These maps are presented in Figures 6-3 through 6-6. The maps were constructed by interpolation between the 177 measured data points.

Similarity among the concentration patterns for carbon monoxide, carbon dioxide and nitrogen oxide is striking at all power settings. The total hydrocarbon pattern is variable and seemingly unrelated to the patterns of the other gaseous exhaust components. The concentration pattern of hydrocarbons at the higher power settings is influenced by the atmospheric background level of 2 ppm or greater. The concentration levels around the periphery of the exhaust nozzle are the levels found in the air which bypass the combustion process. On the other hand, the air which passes through the hot combustion zones of the engine is reduced in hydrocarbon level by incineration.

The hydrocarbon map for maximum continuous power clearly shows the influence of the slow bleed off of hydrocarbons from the sampling lines. The hydrocarbon concentration pattern is different from the hydrocarbon patterns at all other power settings and no longer shows the characteristic symmetry. The effect is large because the concentrations are so low that small changes are magnified. Traverses were begun at the left center of the nozzle cross-section. The traverse probe then was moved horizontally to the right stopping at all the sampling points along the horizontal center line. The data obtained along this initial traverse line is higher than the remainder of the data in the cross-section due to the slow bleed-off of hydrocarbons adsorbed on the interior surfaces of the sampling system. At the time the traverse data were taken, an apparent stable reading was obtained at each sampling point.

Background air influence is also observed in the CO_2 concentration pattern at the idle power level. The lowest level found at idle is in the bypass air region around the outer periphery where the CO_2 level is approximately 200 ppm. The resolution of the CO_2 analyzer at these low levels is poor since the instrument was optimized for the CO_2 concentration range of one to five percent. However, the fact remains that CO_2 background level does influence the concentration pattern.

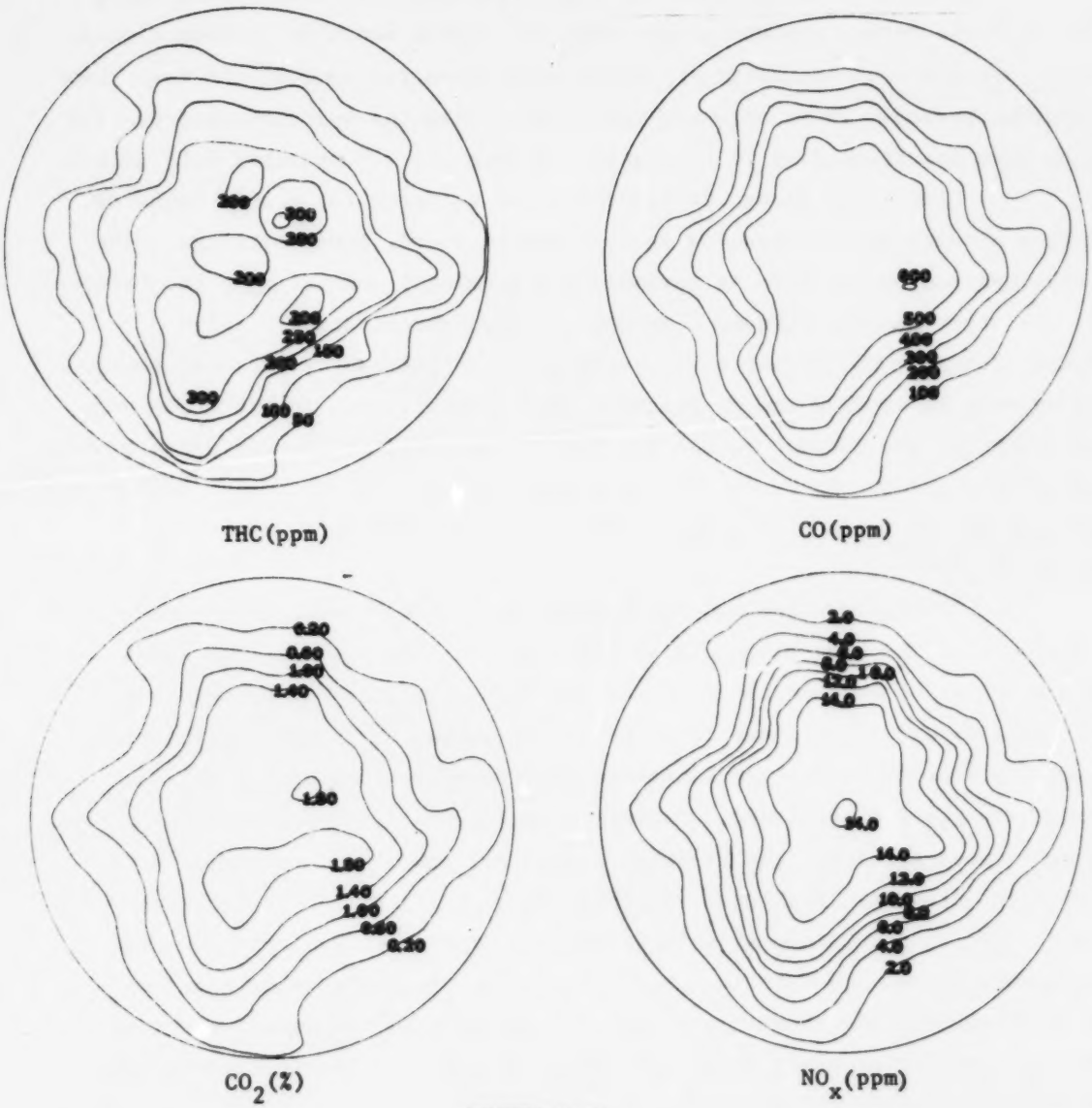
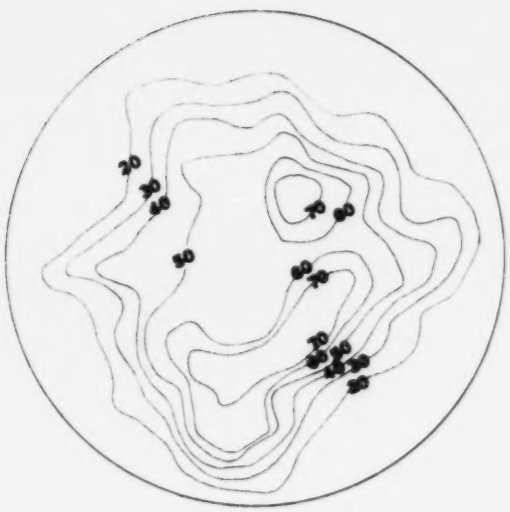


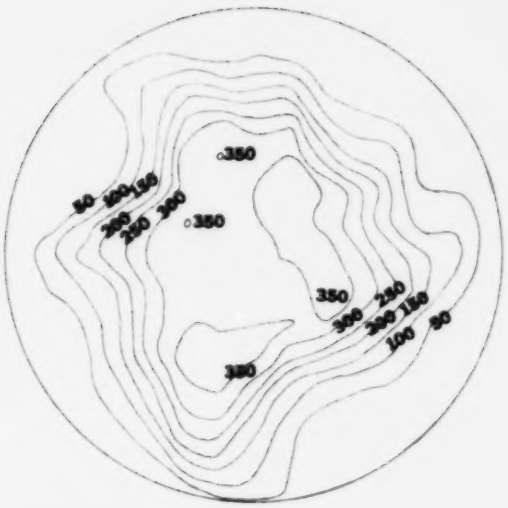
FIGURE 6-3

NOZZLE TRAVERSE - P&W JT8D WITH OLD STYLE COMBUSTORS

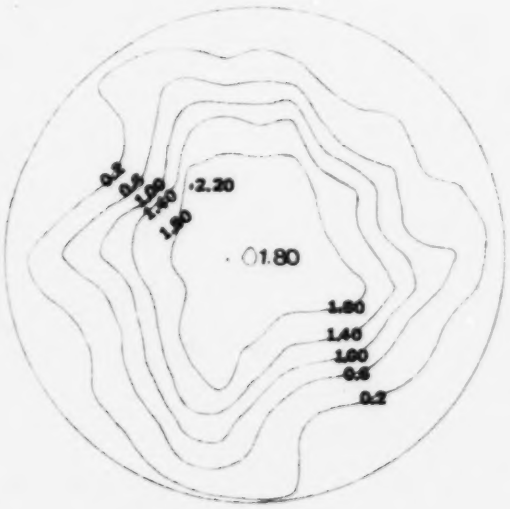
IDLE



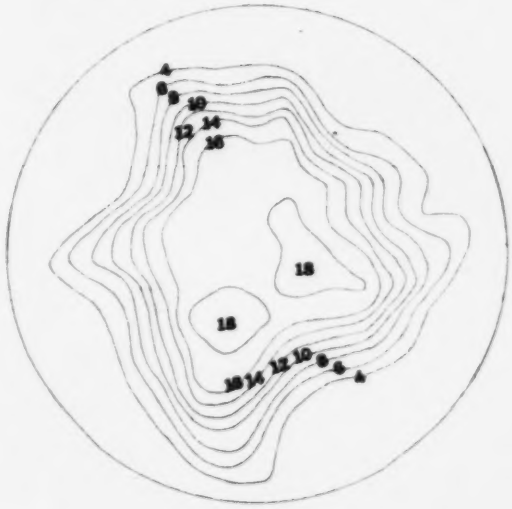
THC(ppm)



CO(ppm)



CO_2(%)



NO_x ppm

FIGURE 6-4

NOZZLE TRAVERSE - P&W JT8D WITH OLD STYLE COMBUSTORS

HOLDING POWER

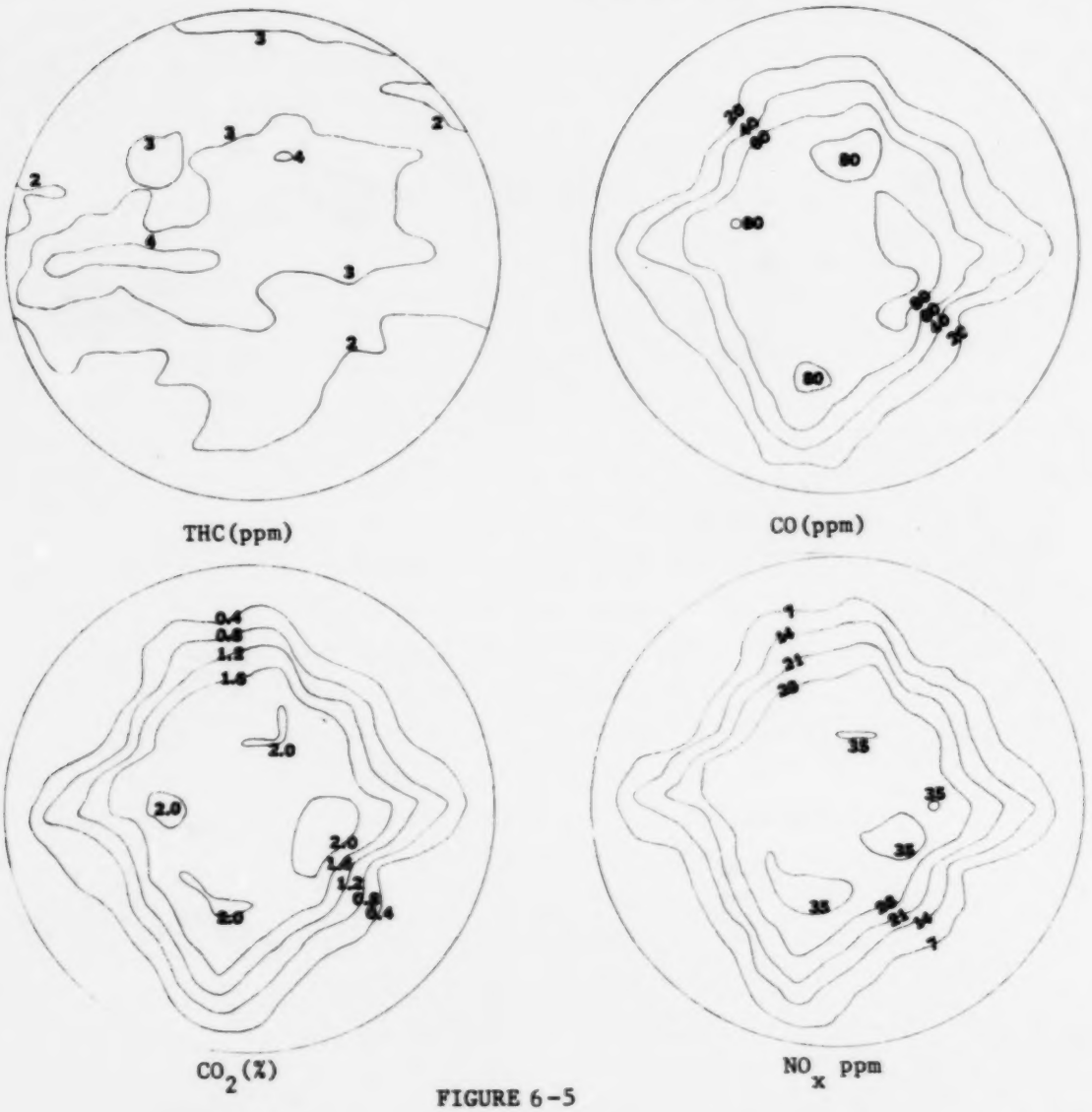


FIGURE 6-5

NOZZLE TRAVERSE - P&W JT8D WITH OLD STYLE COMBUSTORS

APPROACH POWER

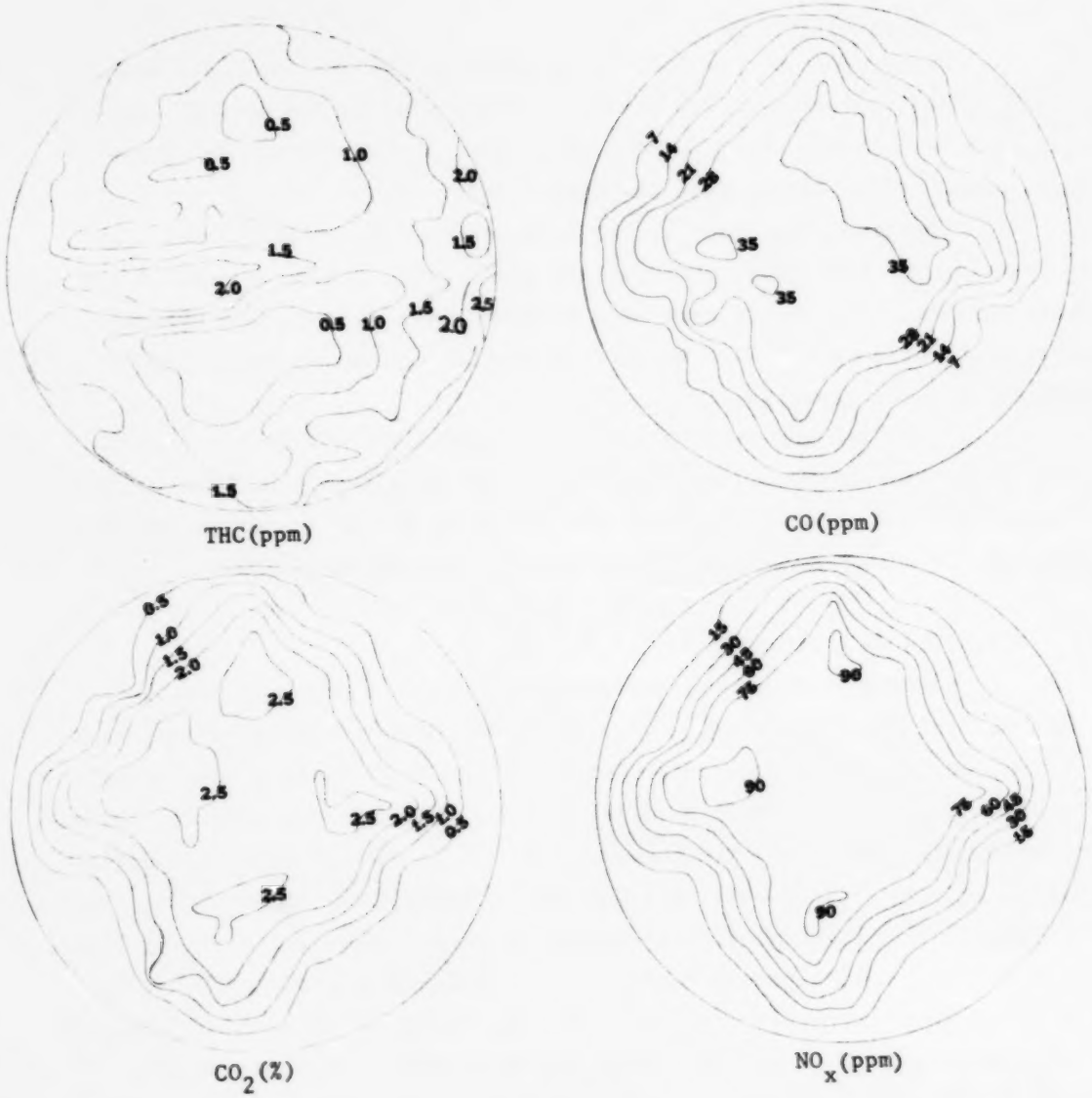


FIGURE 6-6

NOZZLE TRAVERSE - P&W JT8D WITH OLD STYLE COMBUSTORS

MAXIMUM CONTINUOUS POWER

6.2.3 Mixer Traverses

Twenty feet of the mixer pipe described in Section 6.1.2 was placed behind the engine. The pipe was not coupled to the engine. A special 6 inch flanged test section was bolted on the engine end of the mixer pipe. This section held the probes under test.

Traverses were made of the exhaust from the 20 foot mixer pipe by locating the traversing probe at the mixer exit. Traverse data on the mixer exhaust at 61 points were area weighted and concentration averages calculated. Figure 6-7 is a map of the exhaust concentration at idle as emitted from the mixer section.

The mixer was not coupled to the engine directly and a 3 inch annular gap existed between the engine exhaust nozzle and the mixer inlet. Dilution air was induced into this gap resulting in concentration measurements at the mixer outlet which were diluted approximately 20%.

6.3 MIXING PROBE EVALUATION

Several mixing probe designs were evaluated using the test configuration described above. The probes were mounted in the 6 inch test section located at the forward end of the three foot diameter mixer pipe. The mixer pipe was not coupled to the engine. The inlet to the test probes and mixer pipe was positioned from 2 inches to 12 inches behind the engine exhaust nozzle. The traversing probe was located at the mixer pipe outlet. Throughout the probe evaluation, exhaust emission levels at the NAFEC probes mounted in the engine exhaust nozzle were continuously monitored. There were therefore three sampling points and techniques which could be compared simultaneously: 1) The NAFEC probes in the exhaust nozzle area which sampled core engine exhaust, 2) The traverse probe located at the mixer outlet, and 3) The mixing probe located at the engine exhaust plane which was under evaluation to determine if it sampled the average exhaust concentrations at its cross-section.

The mixer pipe, though detached, was located behind the engine. In order to prevent any possibility of engine damage due to backpressure, the engine was not operated above idle. All mixing probe trials were conducted at this operating condition.

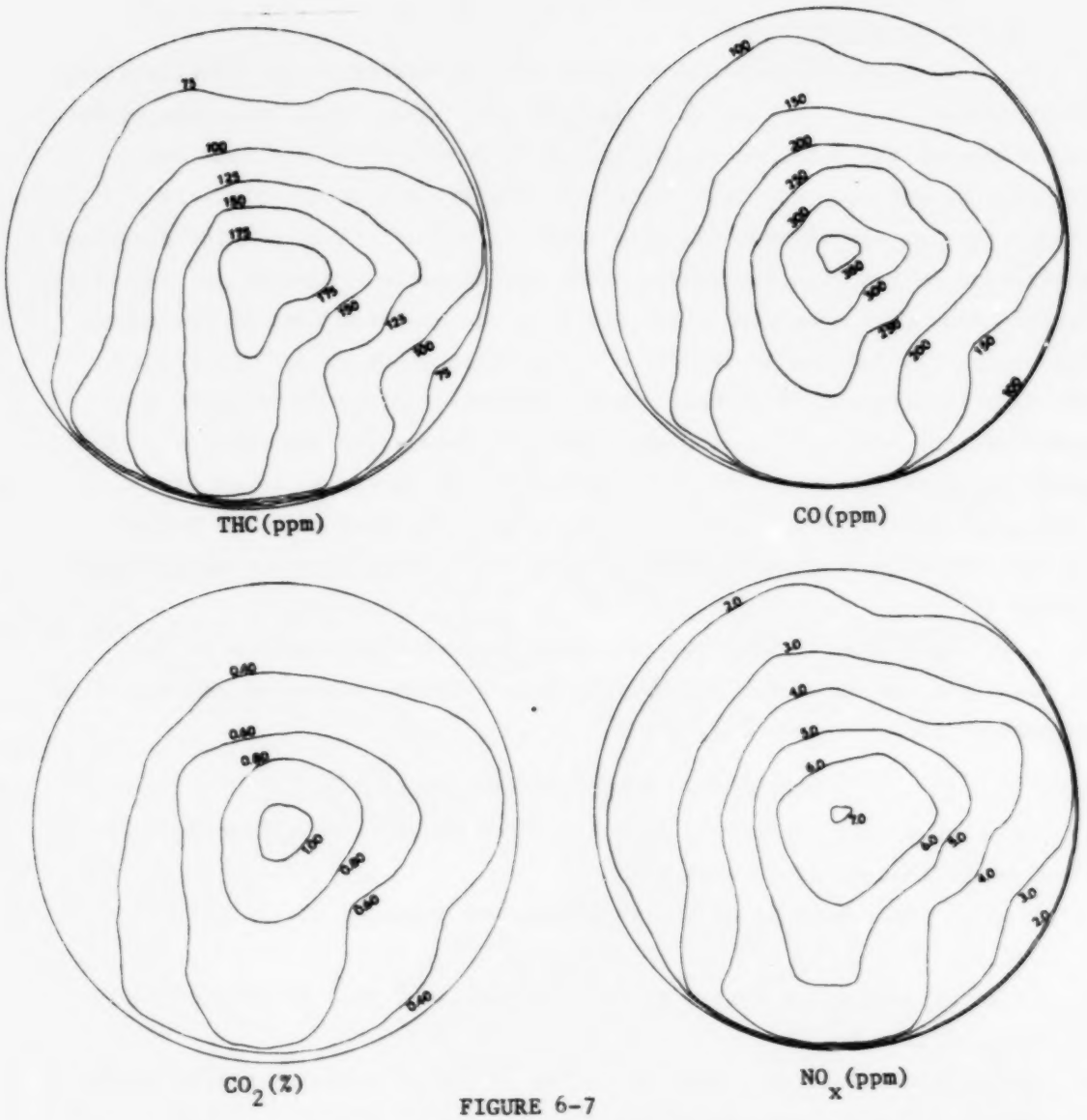


FIGURE 6-7

MIXER TRAVERSE - P&W JT8D WITH OLD STYLE COMBUSTORS

IDLE

6.3.1 Cruciform Probe

A cruciform shaped probe was built according to the specification of Attachment A-1. Two one-inch diameter extra heavy wall stainless steel tubes were welded together in the center to form a cross. A hole was drilled through one tube into the other tube at the center joint. A tubing fitting was welded into this hole. A web of 1/4 inch thick stainless steel four inches wide was welded along the downstream side of the rear tube. Twelve holes were made with a #43 drill on the upstream side of the tubes. The holes were located at centers of equal area based on an "effective" tailpipe diameter of 26 inches. This "effective" diameter had been used previously by EPA in JT8D studies. The cruciform probe was mounted on four angle brackets inside the 6 inch test section which was attached to the mixer pipe inlet. A 1/4 inch stainless steel tube connected the probe central sample port to a bulkhead fitting on the wall of the 6 inch flange section.

Varations of hole patterns were evaluated in addition to the 12 point pattern described above. The hole patterns evaluated are described below and illustrated in Figure 6-8.

TABLE 6-1 HOLE PATTERNS TESTED

1. 12 point pattern on center of equal areas based on an effective engine diameter of 26 inches.
2. 8 point probe made up of the innermost two holes of the 12 point pattern (1).
3. 24 point pattern on center of equal areas based on a 26 inch effective nozzle diameter
4. 24 point combination - made up of the 24 inside holes of the 12 point and 24 point hole patterns above [(1) & (3)].
5. 16 point combination - made up of the sixteen inside points of the 24 point and 12 point patterns.

HOLE POSITIONS ON CRUCIFORM PROBE

	Hole	Radial Position (Inches)
12 pt. probe	A,D,G,K	5.30
	B,E,H,L	9.20
	C,F,J,M	11.85

	Hole	Radial Position (Inches)
24 pt. probe	N,T,Z,FF	3.80
	O,V,AA,GG	6.50
	P,V,BB,HH	8.40
	Q,W,CC,JJ	9.95
	R,X,DD,KK	11.25
	S,Y,EE,LL	12.45

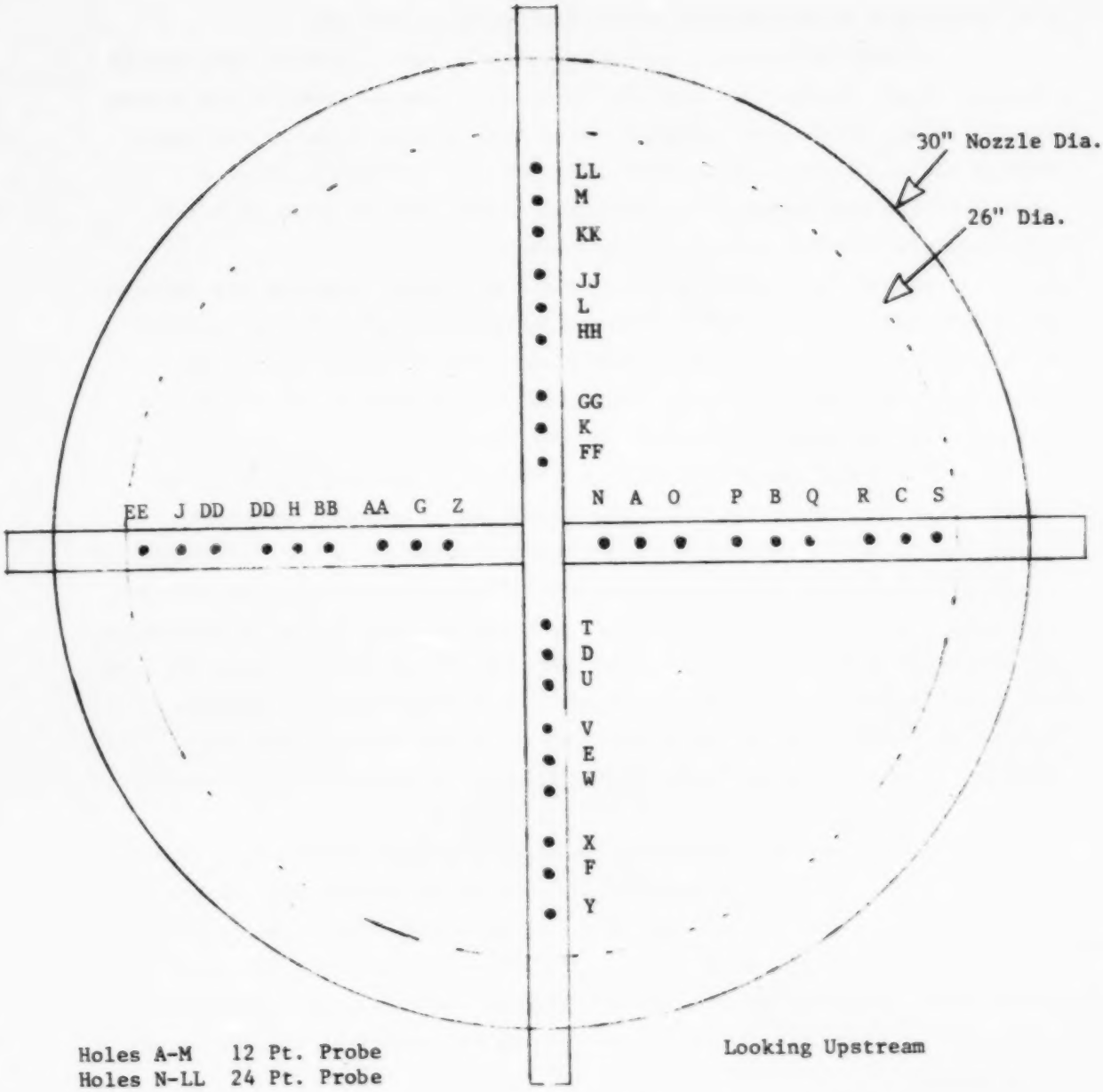


FIGURE 6-8 CRUCIFORM PROBE HOLE PATTERN

6.4 COMPARISON BETWEEN MIXING PROBES AND TRAVERSE AVERAGES

Comparisons between the performance of probe types at idle can be obtained from: 1) the data obtained using the traverse probe at the engine exhaust plane, 2) the data obtained using the traverse probe at the mixer exhaust plane, 3) the data obtained with the NAFEC probes which were mounted in the engine exhaust nozzle, and 4) the data obtained from the cruciform probes which were being evaluated.

In the tests involving the cruciform probes, simultaneous measurements were made with the NAFEC probes. During runs 137, 139, 143 and 144 mixer traverses were also made in addition to the cruciform probe and NAFEC probe readings. Indirect comparisons can be made to the engine traverse averages which were obtained previously.

The probe comparison data is compiled in Table 6-2. The first column lists the probe from which the sample was obtained. The second column describes the position of the cruciform probe which was varied in angular orientation and in distance behind the exhaust plane. The reading number in the third column references the emission data to the corresponding set of engine operational data. More than one set of emission data may have been taken during the time period ascribed to a single reading number. This is followed by the measured emission concentrations and the mass emission rates calculated from a carbon balance as specified in Attachment A-1.

Little may be learned from the concentration data because bypass air entering the outer holes of the cruciform probe dilutes the exhaust sample. Thus, direct comparisons cannot be made with either the concentrations measured with the NAFEC probes which were located in the core engine flow or the average concentrations calculated from the traverse data. The data is best compared by referring to the emission index values (lb/thousand lbs. of fuel).

The percent deviation of each emission index from the index calculated for the traverse average in reading number 124 is listed for the three pollutants. The hydrocarbons and carbon monoxide indices for

TABLE 6-2 PROBE COMPARISON DATA

ALL AT IDLE

Probe	Dist. from Exh. (in.) Angular Position Degrees	Corres. Reading #	Concentrations "Wet" THC ppm-C	CO ppm	CO_2 %	NO_x ppm	Fuel Flow #/Hr.	#/K# Fuel THC	CO	NO_x	% Diff. Relative To #124 Traverse THC	CO	NO_x	Concentration Ratio THC/CO_2	CO/CO_2	NO_x/CO_2
Nozzle Traverse		124	121	233	0.71	5.7	1008	18.7	62.9	2.52	0	0	0	170	328	8.0
Nozzle Traverse		119	127	237	0.71	5.8	1033	19.5	63.7	2.56	4.6	1.3	1.6	178	334	8.1
12 Pt. Probe	8/0	137	169	245	0.67	4.6	998	27.3	69.2	2.13	46.4	10.1	-15.5	252	366	6.8
12 Pt. Probe	8/0	137	168	241	0.67	5.1	998	27.2	68.2	2.37	45.6	8.3	-5.9	250	360	7.6
Mixer Traverse	-	136, 137 138, 139	119	181	0.55	4.0	1003	23.7	62.7	2.28	26.7	0.3	-9.5	217	329	7.2
12 Pt. Probe	8/0	139	154	241	0.67	5.1	1021	25.0	68.3	2.37	34.0	8.5	-5.9	230	360	7.6
8 Pt. Probe	8/0	140	238	397	1.20	9.1	998	21.7	63.2	2.38	16.2	0.4	-5.6	198	331	7.5
NAFEC Probe	-	140	318	489	1.42	10.4	998	24.4	65.5	2.29	30.6	4.1	-9.1	224	344	7.3
NAFEC Probe	-	141	329	501	1.40	9.7	998	25.5	67.9	2.16	38.6	7.9	-14.3	225	358	6.9
8 Pt. Probe	8/0	141	244	409	1.20	8.7	998	22.2	65.0	2.27	18.9	3.3	-9.9	203	341	7.2
Mixer Traverse	-	142, 143 144	118	187	0.53	4.1	998	24.1	67.1	2.42	29.3	6.6	-4.0	222	353	7.7
8 Pt. Probe	8/45	143	193	295	0.80	5.8	998	26.1	69.9	2.25	40.0	11.0	-10.3	241	369	7.2
NAFEC		142	328	489	1.37	9.6	998	26.0	67.7	2.18	39.5	7.6	-13.5	240	357	7.0
8 Pt. Probe	8/45	144	184	273	0.77	5.8	998	25.9	67.3	2.35	38.8	6.9	-6.7	238	354	7.5
12 Pt. Probe-	8/45	145	102	134	0.37	3.0	1021	29.8	68.4	2.52	59.8	8.8	0	276	362	8.1
NAFEC	-	145	357	488	1.40	9.6	1021	27.7	66.1	2.14	48.3	5.0	-15.0	255	348	6.8
12 Pt. Probe	2/45	146	112	153	0.40	2.9	998	30.3	72.1	2.25	62.2	14.6	-10.7	280	382	7.2
12 Pt. Probe	2/22½	147	79	100	0.27	2.2	998	31.7	69.8	2.52	70.0	10.9	0	294	370	8.1
NAFEC	-	147	374	493	1.40	9.6	998	29.0	66.7	2.13	55.1	6.0	-15.5	267	352	6.8
12 Pt. Probe	2/0	148	178	245	0.65	4.6	975	29.7	71.1	2.19	58.9	13.0	-13.1	275	377	7.0
NAFEC	-	148	346	496	1.35	9.1	975	27.8	69.5	2.09	48.7	10.5	-17.1	256	367	6.7
12 Pt. Probe	2/90°	149	196	263	0.67	4.8	998	31.5	73.9	2.21	68.8	17.4	-12.3	292	392	7.1
NAFEC	-	149	380	506	1.40	9.6	998	29.4	68.3	2.13	57.4	8.6	-15.5	271	361	6.8
12 Pt. Probe	12/0	150	166	253	0.67	4.8	1021	26.8	71.4	2.23	43.7	13.6	-11.5	248	378	7.1
NAFEC	-	150	337	493	1.37	9.1	1021	26.7	68.2	2.07	43.0	8.4	-17.8	246	360	6.6
24 Pt. Probe	12/0	151	149	216	0.51	3.6	998	31.3	79.5	2.17	67.8	26.3	-13.9	291	423	7.0
NAFEC	-	151	362	501	1.42	9.2	998	27.7	66.9	2.02	48.2	6.3	-19.8	255	352	6.5
24 Pt. Comb.*	12/0	152	201	300	0.82	5.7	998	26.6	69.3	2.16	42.4	10.2	-14.3	245	366	6.9
NAFEC	-	152	366	493	1.40	9.2	993	28.4	66.7	2.04	51.9	6.0	-19.0	261	352	6.5
16 Pt. Comb.+	12/0	153	252	414	1.15	8.2	998	23.8	68.4	2.22	27.6	8.7	-11.9	219	360	7.0
NAFEC	-	153	366	501	1.40	9.6	998	28.3	67.8	2.13	51.8	7.7	-15.5	261	358	6.5
16 Pt. Comb.	12/45	154	198	300	0.82	5.8	998	26.2	69.3	2.20	40.4	10.2	-12.7	241	366	7.0
NAFEC	-	154	360	501	1.40	9.1	998	27.9	67.8	2.02	49.4	7.7	-19.8	257	358	6.5
16 Pt. Comb.	12/22½	155	194	294	0.77	5.4	975	27.3	72.2	2.18	46.2	14.7	-13.5	252	382	7.0
NAFEC	-	155	371	501	1.40	9.3	975	28.7	67.7	2.06	53.8	7.6	-18.2	265	358	6.6

* 24 Inside points of 24 Pt. & 12 Pt. Pattern
+ 16 Inside points of 24 Pt. & 12 Pt. Pattern
@ Average during traverse

the mixing probes were consistently higher than for the nozzle traverses. The reverse was true for nitrogen oxides. The greatest differences were found in the hydrocarbon data.

Table 6-3 ranks the cruciform probes in the order in which they come closest to the nozzle traverse average. In general the probes whose hole patterns are well within the core engine exhaust agreed best and as the probe hole patterns include more of the outer exhaust stream the more the derived emission rates differ from the nozzle traverse averages.

In Table 6-4 the cruciform probes are compared with the mixer traverse average and ranked in order of closest agreement. The probes with the central patterns again agree more closely with the mixer traverse averages than the probes which include holes in the outer portion of the exhaust. The overall agreement between the cruciform probes and mixer traverse is much better than between the cruciform probes and the nozzle traverses.

6.5 PREDICTIONS FROM TRAVERSE DATA

Predictions based on the point by point nozzle traverse data were made of the emission index which would be calculated from concentrations obtained with multi-point cruciform probes. The predicted values are compared to the actual values obtained with cruciform probes in Table 6-5. All predictions and measurements are at idle power.

The predicted cruciform probe values for carbon monoxide and nitrogen oxides are all within 7% of the nozzle traverse. The predicted hydrocarbon indices for all cruciform probes are lower than the nozzle traverse averages. The measured values for carbon monoxide are from 6 to 25% higher than predicted. The measured hydrocarbons are from 37 to 63 higher, and the measured nitrogen oxides are up to 14% lower than predicted.

It appears that more exhaust was sampled through the outer probe holes where the ratios of hydrocarbons and carbon monoxide to carbon dioxide were greater than at the inner hole locations. This can be seen more clearly from the point by point concentration data for the 12 point probe in Table 6-6. The data were obtained

TABLE 6-3 COMPARISON OF CRUCIFORM PROBES

TO NOZZLE TRAVERSE AVERAGES

Rank	Probe	Orientation	No. of Runs Averaged	% Difference in Emission Index From Exhaust Traverse Average			Average Diff.
				THC	CO	NO_x	
1	8 Pt.	0°	2	17.6	1.8	-7.8	9.1
2	16 Pt. Comb.	0°	1	27.6	8.7	-11.9	16.1
3	8 Pt.	45°	2	39.4	8.9	-8.5	18.9
4	16 Pt. Comb.	45°	1	40.4	10.2	-12.7	21.1
5	24 Pt. Comb.	0°	1	42.4	10.2	-14.3	22.3
	FAA	-	13	47.3	7.2	-16.1	23.5
6	12 Pt.	0°	6	49.6	11.8	-10.7	24.0
7	16 Pt. Comb.	22½°	1	46.2	14.7	-13.5	24.8
8	12 Pt.	45°	2	61.0	11.7	-5.4	26.0
9	12 Pt.	22½°	1	70.0	10.9	0	26.9
10	24 Pt.	0°	1	67.8	26.3	-13.9	36.0

TABLE 6-4 COMPARISON OF CRUCIFORM PROBES

TO MIXER TRAVERSE AVERAGES

Rank	Probe	Orientation	No. of Runs Averaged	% Difference in Emission Index from Mixer Average			Average Diff.
				THC	CO	NO_x	
1	8 Pt.	0°	2	-8.16	-1.26	-1.28	3.57
2	16 Pt. Comb.	0°	1	-0.29	5.41	-5.53	3.74
3	8 Pt. Comb.	45°	2	8.87	5.69	-2.12	5.56
4	16 Pt. Comb.	45°	1	9.66	6.84	-6.38	7.62
5	24 Pt. Comb.	0°	1	11.26	6.81	-8.08	8.72
	FAA	-	13	14.73	3.93	-10.21	9.62
6	12 Pt.	0°	6	16.86	8.41	-4.25	9.84
7	16 Pt. Comb.	22½°	1	14.28	11.23	-7.23	10.90
8	12 Pt.	45°	2	25.77	8.29	1.28	11.78
9	12 Pt.	22½°	1	32.84	7.58	7.23	15.88
10	24 Pt.	0°		31.05	22.43	-7.66	20.38

TABLE 6-5 PREDICTED VERSUS MEASURED
CRUCIFORM PROBE PERFORMANCE

Mode: Idle
All Probes at 0^{o} (arms vertical and horizontal)

Probe (All Cruciform)	Reading No.	Emission Index #/K# fuel					
		Measured			Predicted from Nozzle Traverse		
		THC	CO	NO_x	THC	CO	NO_x
12 Pt.	137	27.33	69.24	2.13	17.72	63.88	2.46
12 Pt.	148	29.68	71.14	2.19	17.72	63.88	2.46
8 Pt.	140	21.69	63.17	2.38	15.86	59.26	2.36
24 Pt.	151	31.32	79.46	2.17	18.01	64.64	2.47
24 Pt. Comb.	152	26.59	69.32	2.16	16.89	63.00	2.50
16 Pt. Comb.	153	23.83	68.41	2.22	15.56	61.28	2.53
Nozzle Trav. Avg.	124	18.67	62.92	2.52	-	-	-
Mixer Trav. Avg.	142,143 144	24.1	67.1	2.42			

TABLE 6-6 PREDICTED CONCENTRATIONS FOR TWELVE POINT PROBE AT IDLE BASED ON NOZZLE TRAVERSE DATA (RUN 124)

Hole	THC ppm	CO ppm	NO_x ppm	CO_2 %	THC/CO_2	CO/CO_2	NO_x/CO_2
				OUTER RING			
C	148	235	4.4	0.59	252	401	7.6
F	127	195	3.5	0.49	260	399	7.2
J	73	188	3.6	0.53	137	353	6.7
M	53	91	2.3	0.25	211	362	9.2
Ave.	100	177	3.5	0.47	215	381	7.4
				MIDDLE RING			
B	181	325	7.3	0.90	201	361	8.1
E	223	346	6.7	0.95	235	364	7.1
H	157	319	6.2	0.93	169	343	6.6
L	131	309	7.9	0.93	141	332	8.5
Ave.	173	325	7.0	0.93	186	349	7.6
				INNER RING			
A	221	513	13.4	1.64	135	313	8.1
D	260	545	13.9	1.77	147	308	7.8
G	218	505	12.3	1.62	134	312	7.6
K	199	540	15.0	1.72	116	314	8.7
Ave.	225	526	13.6	1.69	154	312	8.1
Overall Average	166	342	8.0	1.03	162	334	7.8
Measured with 12 point probe							
Run 137	169	245	4.6	0.67	253	367	6.9
Run 148	179	245	4.6	0.64	279	383	7.2

from the nozzle traverse of Run 124 by interpolation. This assumes that the flow of gases from the nozzle traverse location (2 inches downstream of the plane of the nozzle) to the mixing probe location (2 to 12 inches downstream of the plane of the nozzle) was perfectly horizontal.

The carbon dioxide concentration obtained with the mixing probe is approximately midway between the concentrations predicted for the outer and middle rings. This appears to confirm that greater gas volumes were sampled at the outer holes as compared to the middle and inner holes. However, this does not explain the high hydrocarbon and carbon monoxide concentrations found since it is seen that the ratios of these pollutants to carbon dioxide are greater than would be expected for any point at or within the outer ring. The explanation offered for this anomalous data relates to the position of the mixing probe in the 36 inch diameter mixer tube. It is known that dilution air entered the mixer tube because the tube was not coupled to the nozzle. The volume of dilution air was estimated to be 20% of the turbine exhaust volume by comparing the mixer and nozzle traverse carbon dioxide concentrations. It is now proposed that as this dilution air entered the mixer tube it distorted the plume coming from the nozzle. The net effect was that some of the gas in the extreme outer portion of the nozzle plume was driven or diffused inward to the outer sampling holes of the 12 point cruciform probe. Since the outer portion of the nozzle plume was composed of exhaust with higher hydrocarbon and carbon monoxide to carbon dioxide ratios than the inner portion, the ratios found in the sample from the cruciform probe were higher than predicted. While there is no firm evidence that this proposed explanation is correct, it appears to be the only way to explain the measured data.

6.6 TRAVERSE AVERAGES VERSUS NAFEC PROBE READINGS

The nozzle traverse averages are compared to the NAFEC probe readings at several load conditions in Table 6-7. The data for the NAFEC probe are given for test runs other than the nozzle traverse runs because leaks in the NAFEC probe sample system gave erroneous data for that probe during the nozzle traverse runs. The emission indices show the greatest

TABLE 6-7 TRAVERSE AVERAGES VERSUS NAFEC PROBE

Mode	Probe	Read. No.	EPR	Concentration				#/K# fuel		
				THC	CO	CO_2	NO_x	THC	CO	NO_x
Idle	TA	124	1.042	120.9	237	.71	5.8	18.64	63.80	2.56
	FAA	110	1.041	345	508	1.42	9.8	26.35	67.76	2.15
Holding	TA	125	1.0705	30.8	147	.75	7.1	4.61	38.44	3.05
	FAA	97	1.065	148.5	345	1.40	9.0	11.78	47.79	2.05
Approach	TA	121	1.302	2.52	35	.83	14.6	.348	8.43	5.77
	FAA	116	1.284	4.3	82	1.62	26.2	.304	10.11	5.31
MCP	TA	123	1.873	1.2	18	1.29	43.1	.107	2.80	11.00
	FAA	113	1.887	2.0	27	2.38	80.5	.097	2.28	11.14

differences for all pollutants at the holding condition. Except for the 41% difference in hydrocarbons indices at idle, the differences in the emission indices for the three pollutants at conditions other than holding did not exceed 20%.

6.7 CARBON BALANCE CALCULATION OF EXPECTED CARBON DIOXIDE CONCENTRATIONS

As a check on the representativeness of the exhaust concentration data collected using the various probes described above carbon balance calculations were made of the expected exhaust carbon dioxide concentration based on the measured engine fuel and air consumption. The ratio of the mass of carbon dioxide produced to fuel burned from a CxHy fuel is:

$$\frac{\#CO_2}{\#\ \text{fuel}} = \frac{44x}{12\ X + y}$$

The fuel used during the reported program had a measured hydrogen/carbon mole ratio of 1.9. The carbon dioxide produced from this fuel calculated from the above equation will be 3.165 # CO_2/fuel. Now since:

$$\frac{\#CO_2}{\#\ \text{fuel}} \cdot \frac{\#\ \text{fuel}}{\#\ \text{air}} = \frac{\#CO_2}{\#\ \text{air}}$$

and the volume fraction is: $\frac{\#CO_2}{\#\ \text{air}} \cdot \frac{29}{44} = \frac{\text{mol } CO_2}{\text{mol air}}$

then the average concentration of CO_2 in percent by volume which we would expect to find in the gas turbine exhaust would be:

$$\%\ CO_2 = \frac{F}{A}\ (3.165)\ \frac{29}{44}\ \frac{100}{3600} = .05794\ \frac{W_F}{W_a}$$

where: W_F is the engine fuel flow in lbs/hr., and W_a is the engine air flow in lbs/sec. The engine air flow was measured at the bell mouth inlet to the JT8D gas turbine.

Table 6-8 compares the expected average CO_2 concentrations with the actual measured concentrations for several probes and probe positions tested. The nozzle traverse averages agree very well with the calculated CO_2 levels. This lends credence to the validity of the assumption of equal flow at each of the 177 nozzle traverse points.

TABLE 6-8 CALCULATED AVERAGE CO_2 EXHAUST CONCENTRATIONS COMPARED TO MEASURED VALUES

Power Setting	Reading No.	W_F #/Hr.	W_a #/Sec.	Calc. CO_2 (%)	Measured CO_2 Concentration (%) NAFEC	12 Pt.	12 Pt. Position	Nozzle Traverse	Other	Probe Position
Idle	124	1008	81.5*	.71				.71		
	137	997.8	81	.71		.67	0°			
	139	998.5	81	.71		.67	0°			
	140	1021.4	81	.73	1.42				1.20	8 Pt. / 0°
	141	997.9	81	.71	1.40				1.20	8 Pt. / 0°
	142	997.9	83	.70						
	143	998.5	81	.71	1.37				.80	8 Pt. / 45°
	144	998.5	85	.68					.77	8 Pt. / 45°
	145	1021.4	83	.71	1.40	.37	45°			
	146	998.5	83	.70		.40	45°			
	147	998.5	81	.70	1.40	.27	22½°			
	148	975.0	83	.68	1.35	.65	0°			
	149	997.9	83	.70	1.40	.67	90°			
	150	1020.8	83	.71	1.37	.67	0°			
	151	997.9	81	.71	1.42				.51	24 Pt. / 0°
	152	997.9	81	.71	1.40				.82	24 Pt. Comb. / 0°
	153	997.9	81	.71	1.40				1.15	16 Pt. Comb. / 0°
	154	997.9	81	.71	1.40				.82	16 Pt. Comb. / 45°
	155	975.0	81	.70	1.40				.77	16 Pt. Comb. / 22½°
Holding	125	1347.4	109.9	.71				.71		
Approach	121	2957.2	212	.81				.83		
MCP	123	6916.3	303.8	1.32				1.29		

* Average during run

7.0 BASELINE MEASUREMENTS

The contributions of operating conditions, the operating technique and the instrumentation to variations in emissions measurements were determined from the data acquired in the tests on the JT8D engine. The effect of approach to power was determined by examining the data acquired during engine calibration runs where the engine was operated at distinct power levels over its operating range and the direction of approach to the power setting was noted. The run-to-run variation at the same power setting was calculated from the emissions data. This run-to-run variation illustrates the combined uncertainty level of the instrumentation and engine operation. The effect of variation in fuel flow was illustrated by its effect on the uncertainty of the calculated mass per mode values.

7.1 RUN-TO-RUN VARIATION

The overall variability of the emissions measurements can be demonstrated using the data acquired during the probe evaluation series of tests. All these tests were made at idle power. The engine was shut down, the probe configuration changed and the engine restarted between each test. The time the engine was shut down varied from 15 minutes to overnight (approximately 16 hours). At each test point emissions data were obtained from the NAFEC probes which remained unchanged in position or configuration through the series of tests. The ambient conditions varied over only a small range of winter levels.

Table 7-1 contains the emission index values calculated from the data taken on 13 consecutive engine runs at idle power. Reading number 142, 144 and 146 correspond to additional data taken during mixer traverses.

The greatest uncertainty was found in the hydrocarbon data where the coefficient of variation was 5.3%. The coefficients of variation for carbon monoxide and nitrogen oxides were 1.5% and 3.5%.

The engine operating parameters (thrust, fuel flow and EPR) exhibited similar variability with the thrust coefficient of variation largest at 4.8%. Removal of the obvious thrust outlier of Run 147 would reduce the variation considerably. The fuel flow coefficient of variation was low (1.3%) and the EPR coefficient of variation was very low (.008%).

TABLE 7-1 RUN-TO-RUN VARIATION IDLE POWER SETTING

FAA Probe Data - Scott Readings

Run No.	#/K# Fuel THC	CO	NO_x	EPR	Thrust #'s	Obs. Fuel Flow #/Hr.
140	24.39	65.51	2.29	1.040	757.5	997.9
141	25.50	67.92	2.16	1.040	782.7	997.9
143	26.05	67.72	2.18	1.041	808	998.5
145	27.69	66.09	2.14	1.041	808	1021.4
147	28.96	66.67	2.13	1.040	707	998.5
148	27.77	69.53	2.09	1.040	797.9	975.0
149	29.39	68.34	2.13	1.040	797.9	997.9
150	26.70	68.21	2.07	1.040	828.2	1020.8
151	27.67	66.87	2.02	1.040	828.2	997.9
152	28.36	66.70	2.04	1.040	828.2	997.9
153	28.34	67.75	2.13	1.041	808	997.9
154	27.89	67.78	2.02	1.043	848.4	997.9
155	28.72	67.73	2.06	1.043	848.4	975.0
$\bar{X}$	27.49	67.45	2.11	1.040	803.7	998.7
σ^2	2.11	1.12	.005	$.72 \times 10^{-6}$	1487.2	178.4
σ	1.45	1.05	.075	$.85 \times 10^{-3}$	38.6	13.4
CV %	5.3	1.5	3.5	.008	4.8	1.3

7.2 EFFECT OF APPROACH-TO-POWER

The engine power setting just previous to that at which a measurement is made may influence the emissions data at that test point. Measured engine emission rates of carbon monoxide, nitrogen oxides and total hydrocarbons are plotted against engine pressure ratio (EPR) in Figures 7-1, 7-2 and 7-3. EPR is a convenient measure of engine power. Emission data from both smoky and smokeless combustors are included. The curves drawn through the data points are intended for reference only.

The "up" symbols designate those data points which were obtained when the engine power setting was increased up to the data point level. The "down" symbols designate data points where the engine power was decreased from a higher power setting to arrive at the correct level for the data point.

The direction of approach to power did not have a significant effect on the carbon monoxide and nitrogen oxide emission indices (Figures 7-1 and 7-2). However, the total hydrocarbon indices were heavily dependent on the approach-to-power. At the higher power settings there is considerable scatter. Since the carbon monoxide and nitrogen oxides show no effect of approach-to-power, it is possible that the apparent hydrocarbon effect is not caused by changes in the engine emissions themselves. The hydrocarbon measurements would be affected by the condition of the sample line. The concentrations of hydrocarbons increase by a factor of 1000 from high power settings to low power settings. The heated sample lines absorb hydrocarbons during the low power sampling and require some time to desorb those hydrocarbons when the power setting is increased and the exhaust hydrocarbon level drops sharply. A possible cure for this problem is to use very clean lines and to wait until the hydrocarbon level is stable for a few minutes before logging the concentration data for that data point.

7.3 EFFECT OF VARIATIONS IN ENGINE THRUST AND FUEL FLOW

The measurements of engine thrust and fuel flow were performed at NAFEC with transducers whose accuracy is $\pm$ 0.25%. The accuracy of the actual

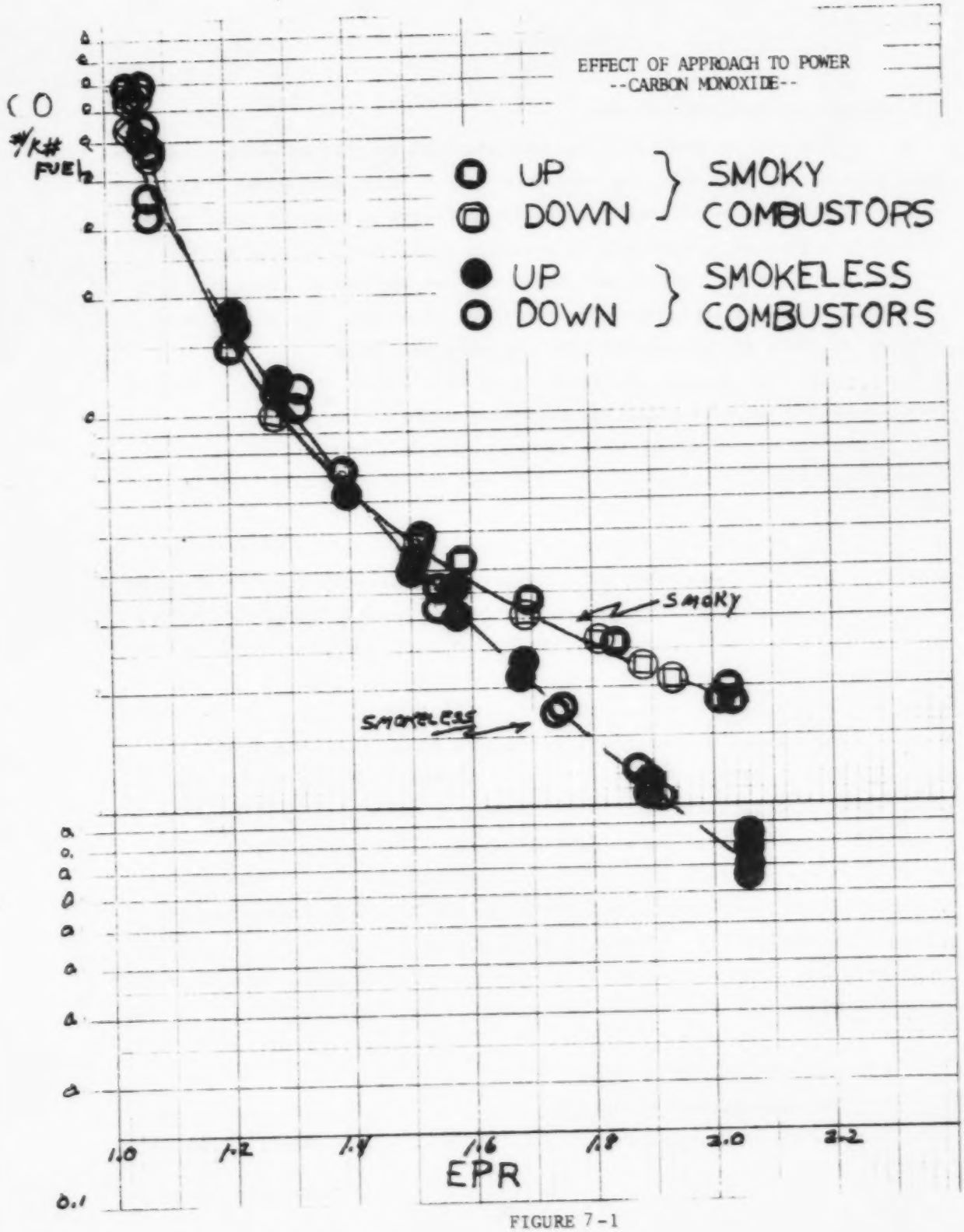
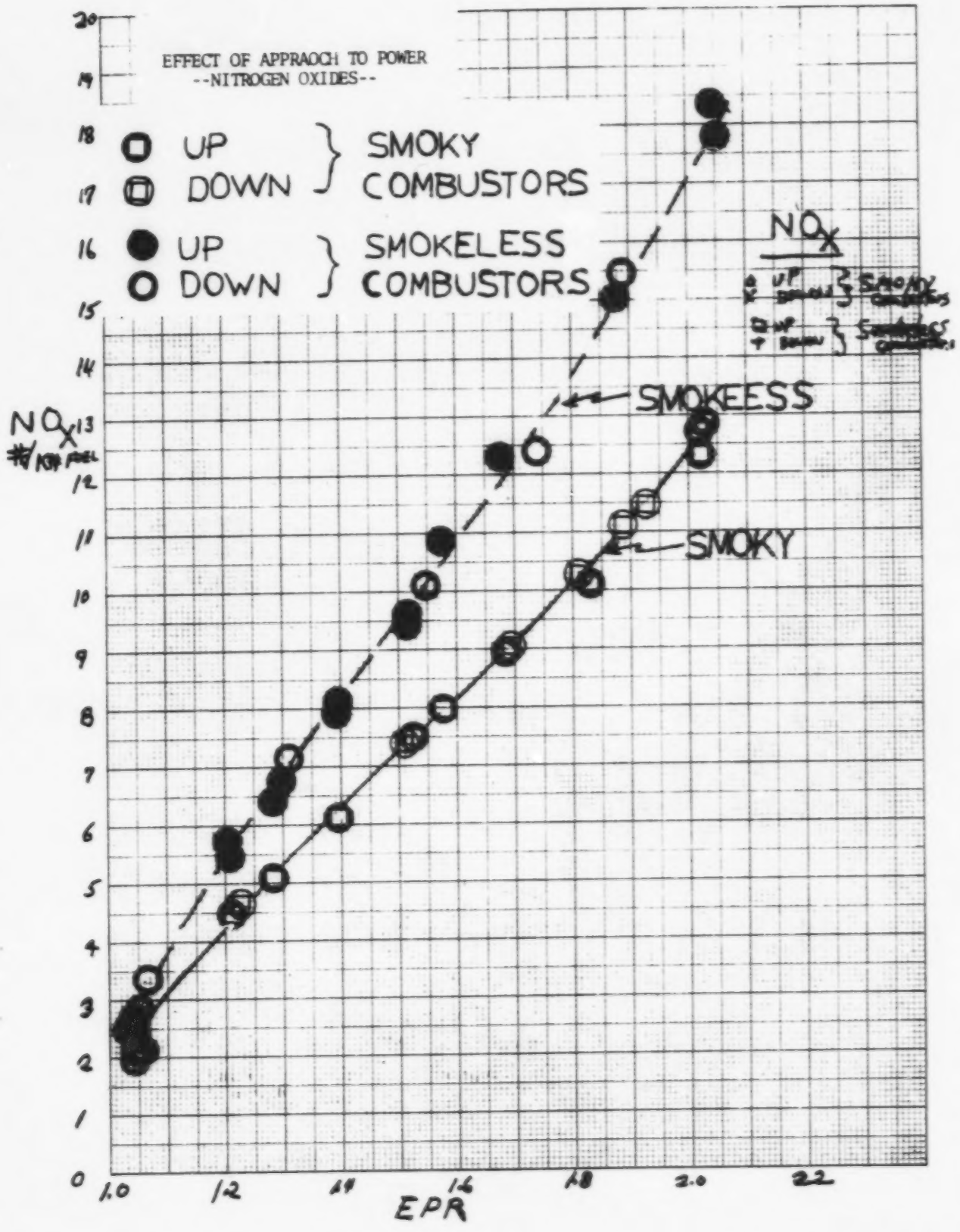

EFFECT OF APPROACH TO POWER
--CARBON MONOXIDE--
CO
#/K# FUEL
UP
DOWN
SMOKY COMBUSTORS
UP
DOWN
SMOKELESS COMBUSTORS
SMOKY
SMOKELESS
1.0
1.2
1.4
1.6
1.8
2.0
2.2
EPR
0.1

FIGURE 7-1


EFFECT OF APPRAOCH TO POWER
--NITROGEN OXIDES--
UP
DOWN
SMOKY COMBUSTORS
UP
DOWN
SMOKELESS COMBUSTORS
NOx
SMOKEESS
SMOKY
NOx #/KG FUEL
EPR
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
1.0
1.2
1.4
1.6
1.8
2.0
2.2

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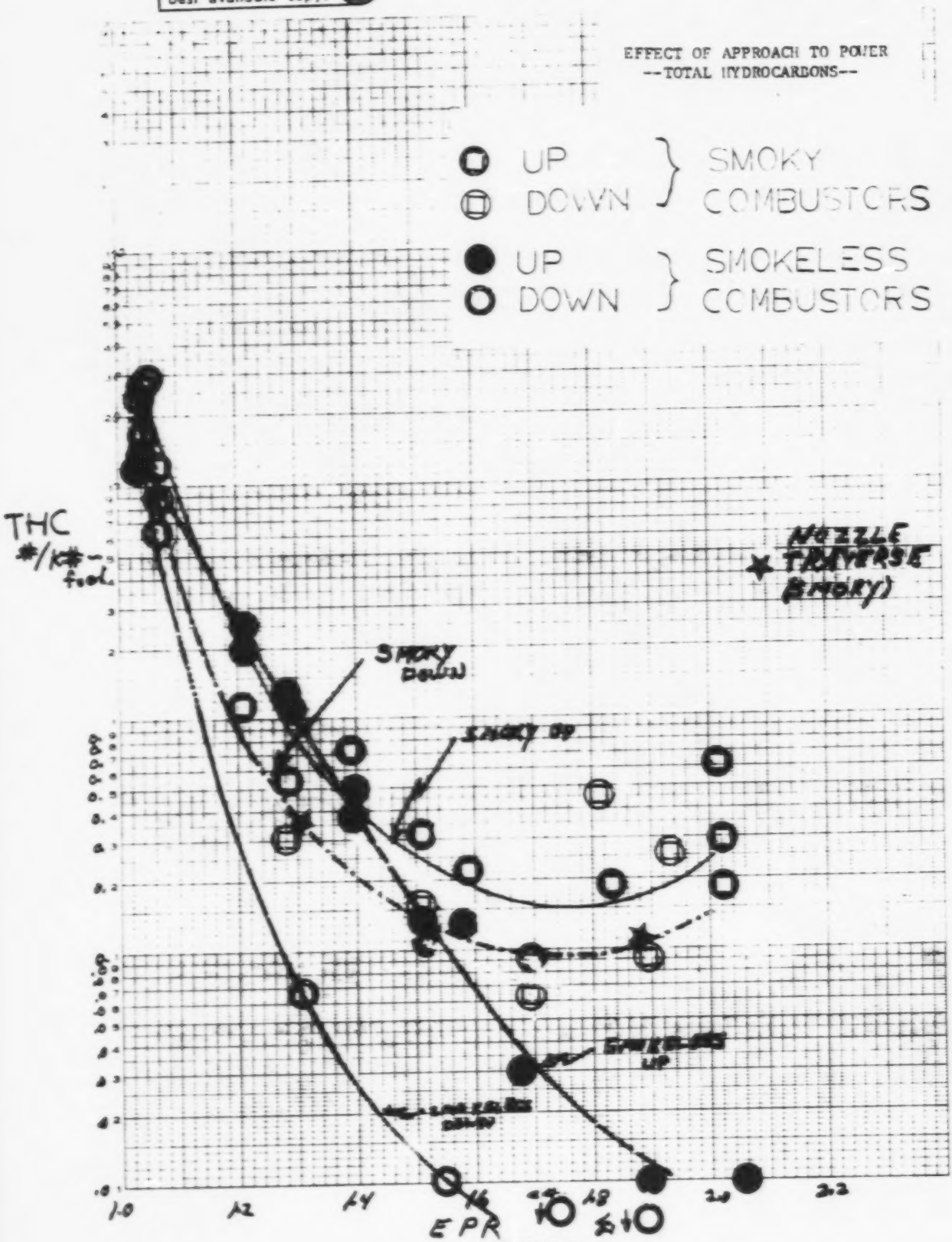

FIGURE 7-3

measurement of thrust was determined at NAFEC to be ±3%* over all thrust levels. The degradation of accuracy in the measurement is due to the error in the conversion of the transducer signals into electrical outputs and the errors associated with recording those signals as well as the effects of engine thrust unsteadiness due to the hunting in the fuel control system. The fuel flow accuracy was determined at NAFEC to be ± 2.25% mostly due to the hunting action in the fuel control system.

The uncertainty in the calculation of mass per mode may be estimated from the experimentally determined variances shown in Table 7-1 by standard statistical methods.+ The mass per mode for the taxi/idle out mode is calculated from the equation:

Mass/mode = emission rate(#/# fuel) x fuel flow (#/Hr) x TIM (Hr)

The variance in the mass/mode calculation is:

$$V(\text{mass/mode}) = \left[TIM \cdot (\overline{CO})\right]^2 \cdot V(F) + \left[TIM \cdot (F)\right]^2 \cdot V(\overline{CO})$$

where: TIM = time in mode

$\overline{CO}$, $\overline{THC}$, $\overline{NO_x}$ = emission rates in #/# fuel of CO, THC and NO_x

F = fuel flow rate

V(CO) = variance in the CO measurement

V(F) = the variance in the fuel flow measurement.

Using the mean values of fuel flow and emission rates and the variances in fuel flow and emission rates in Table 7-1, the variance in the calculated mass per mode values was determined. The variance of the mass per mode values is tabulated in Table 7-2. Also tabulated in Table 7-2 are the mean value of mass per mode which was calculated using the mean emission rates and mean fuel flow and the standard deviation which is the square root of the variance. The coefficient of variation was calculated from the

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* Personal communication with G. Slusher, NAFEC.

\+ Statistical Methods in Research and Production, Halfner Publishing Co., New York, New York, 1972

mean and standard deviation values for each emission parameter.

The coefficient of variation of the product of fuel flow and emission rates of hydrocarbons in pounds per mode increased 14.5% over the coefficient of variation of the emission rate of total hydrocarbons in pounds per thousand pounds of fuel. Similarly the coefficient of variation in the pounds per mode of carbon monoxide and nitrogen oxides increases 36.7% and 8.5% over the coefficient of variation in the values of pounds per thousand pounds of fuel.

TABLE 7-2 VARIANCE IN THE CALCULATION OF MASS PER MODE (IDLE)

		THC	CO	NO_x
Mean	$\bar{X}$	7.75	21.2	.67
Std. Deviation	σ	.47	.44	.025
Variance	σ^2	.221	.190	6.4×10^{-4}
C.V.	%	6.07	2.05	3.8

8.0 AMBIENT CONDITIONS

It is necessary to determine the effect of ambient temperature and humidity on emission rates from turbine engines so that emission measurements made at various ambient conditions can be corrected to equivalent values at a standard condition. Temperature and humidity effects are best determined in a controlled atmosphere test cell. This was not available at NAFEC, but indications of ambient effects can be gleaned from plots of data obtained during the various test runs. Figures 8-1 through 8-3 depict emission indices as a function of humidity at idle, approach and maximum continuous power. Temperature effects are shown similarly in Figures 8-4 through 8-6. At idle hot and cold runs are denoted. A "cold" idle is one in which the run was first idle after starting the engine and was the only power setting at which the engine had been operated after the start of the engine. A "hot" idle occurred when the engine was brought down to idle from some higher power setting. All data shown are from the NAFEC probes because these were common to all test runs. It is apparent that with increasing temperature and/or humidity there were usually decreases in hydrocarbons and carbon monoxide and increases in nitrogen oxides. The greatest change was noted at approach power. The observed effect ranged from a 2.5 to one change in hydrocarbons with a 1.5 to one change in carbon monoxide and a 1.15 to one change in nitrogen oxides at approach to a slight change at maximum continuous power over the range of temperatures and humidities sampled.

The primary problem in separating temperature and humidity effects results from the fact that temperature and humidity followed similar patterns of increase or decrease from run to run. Thus, it is not clear which parameter caused the variation in emission indices. Based on experience it would seem that temperature of the inlet air should have a greater effect on combustion than humidity.

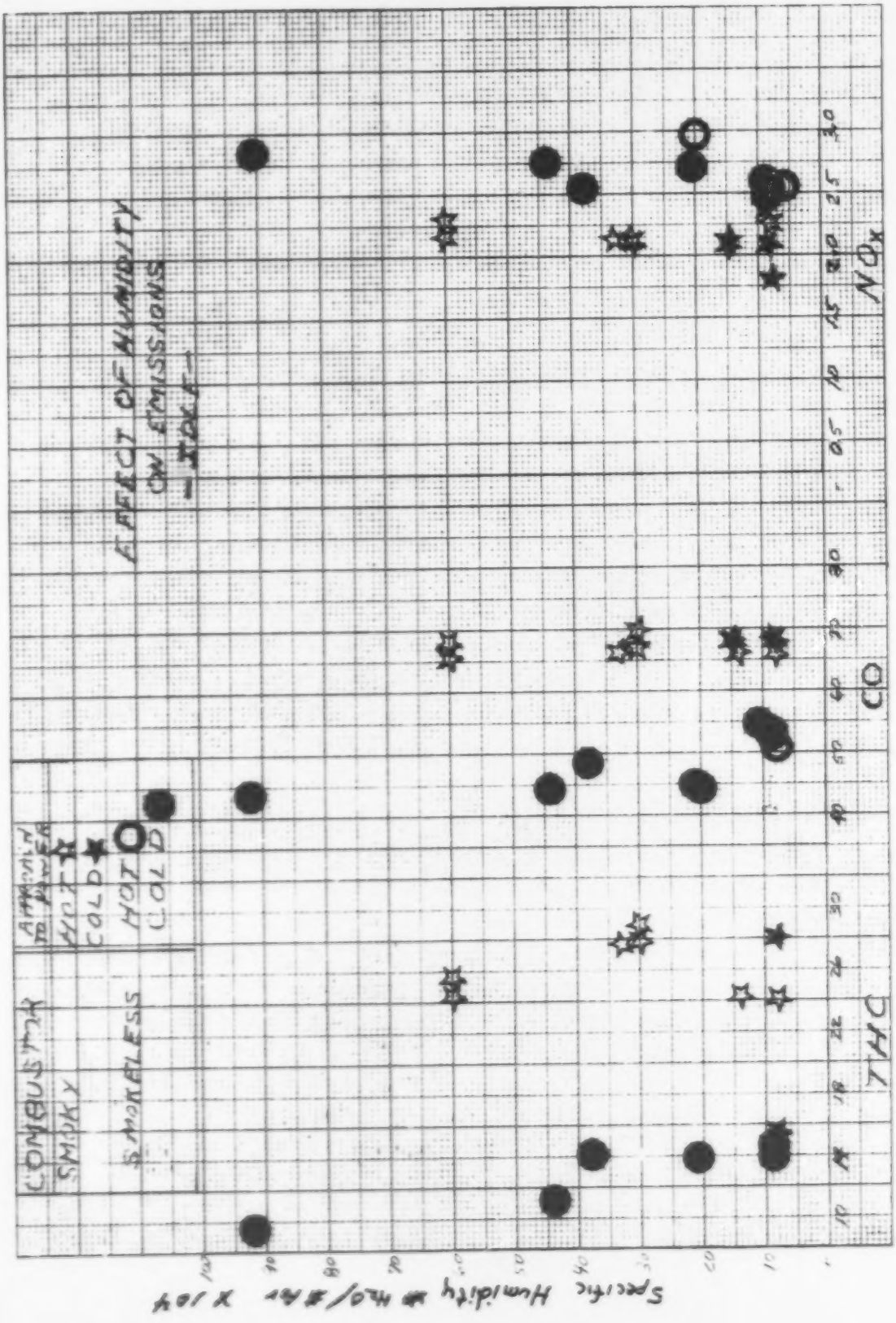
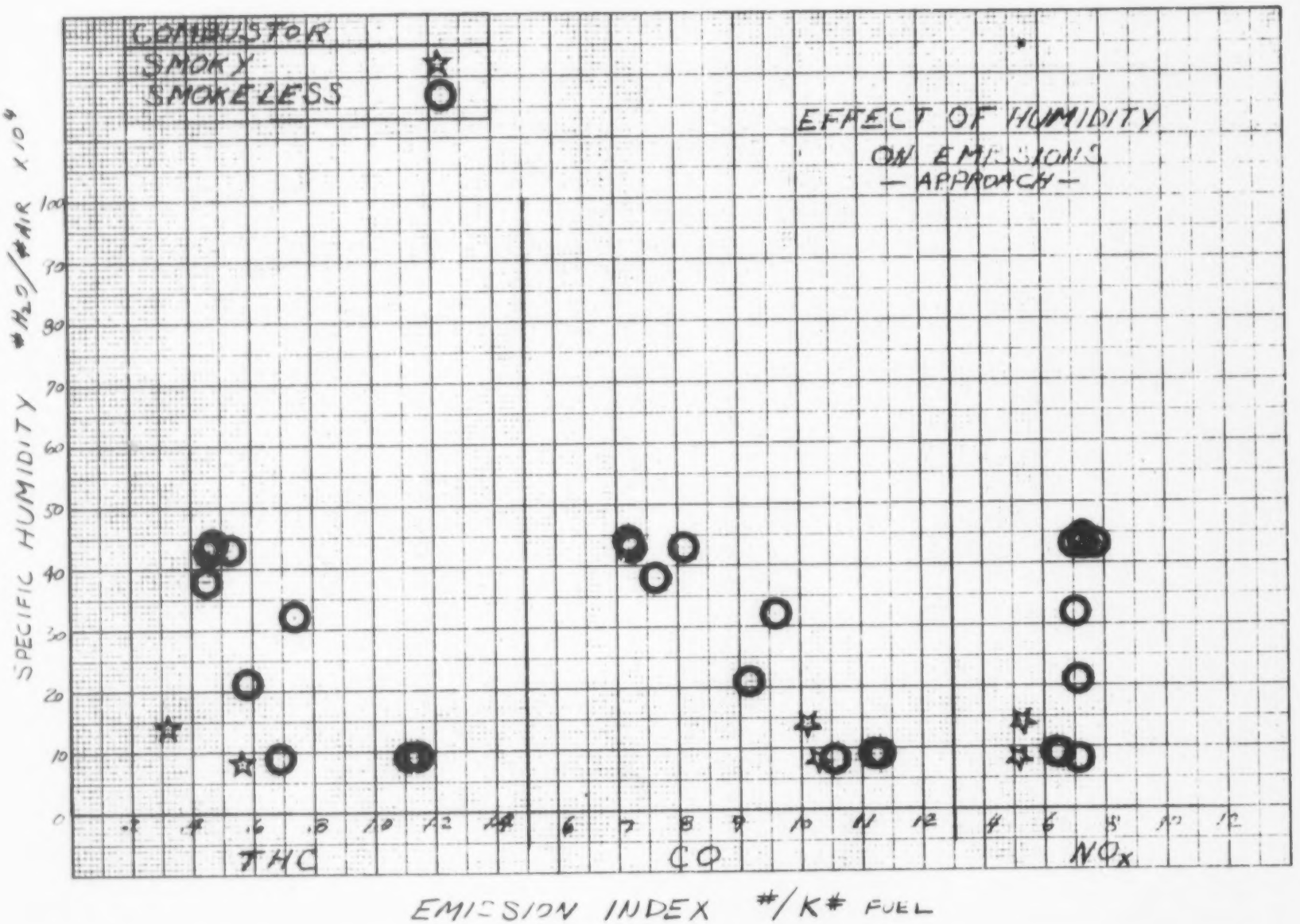

COMBUSTOR
SMOKY
SMOKELESS
AMBIENT
HUMIDITY
COLD
HOT
COLD
EFFECT OF HUMIDITY
ON EMISSIONS
—STACK—
Specific Humidity = H2O/Air X 10⁴
THC
CO
NOx
Emission Index #/1000 fuel

FIGURE 8-1


COMBUSTOR
SMOKY
SMOKELESS
EFFECT OF HUMIDITY
ON EMISSIONS
— APPROACH —
SPECIFIC HUMIDITY #H2O/#AIR X 10⁴
0
10
20
30
40
50
60
70
80
90
100
THC
CO
NOx
EMISSION INDEX #/K# FUEL

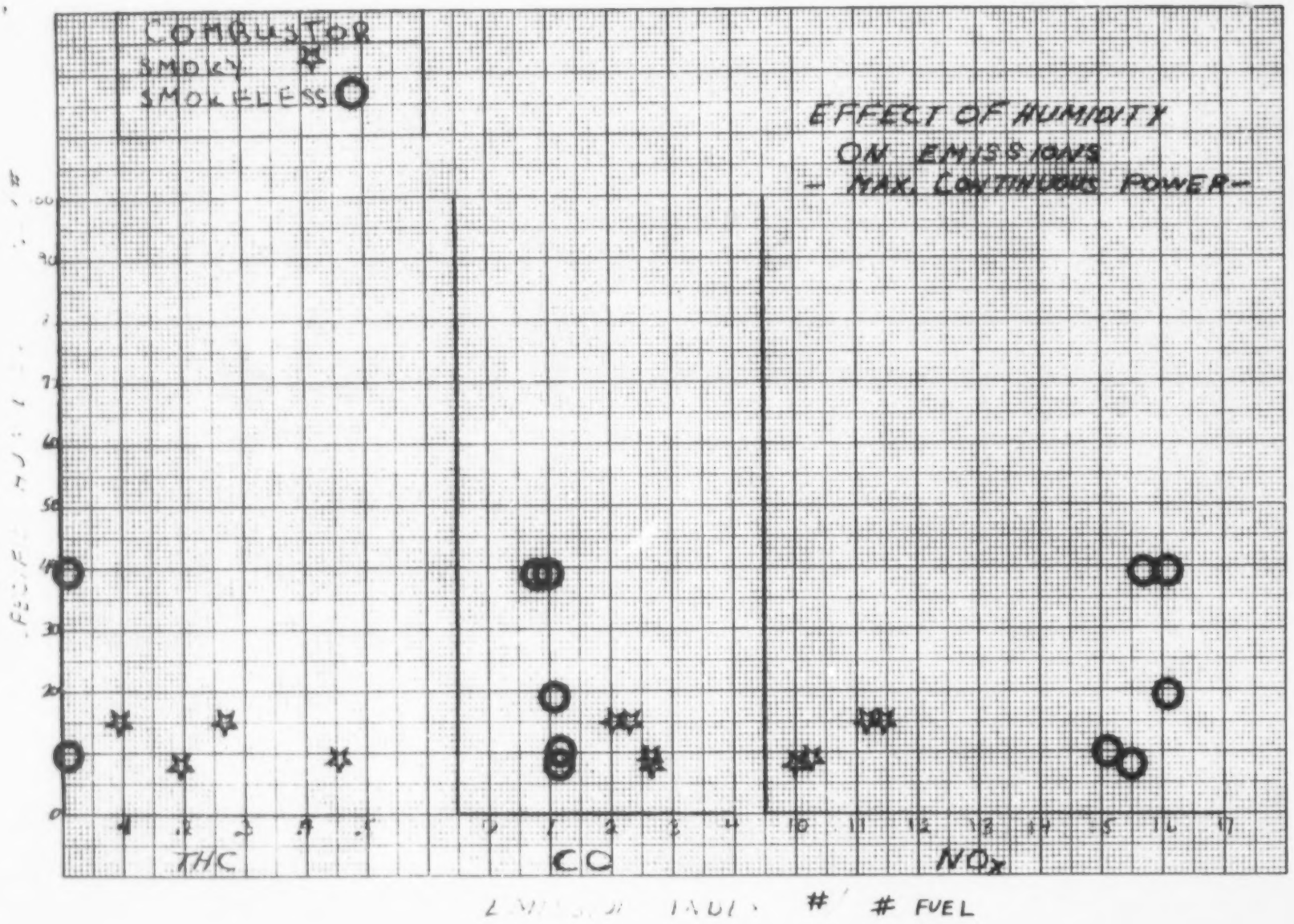

COMBUSTOR
SMOKY
SMOKELESS
EFFECT OF HUMIDITY
ON EMISSIONS
— MAX. CONTINUOUS POWER —
THC
CO
NOx
FUEL

FIGURE 8-3

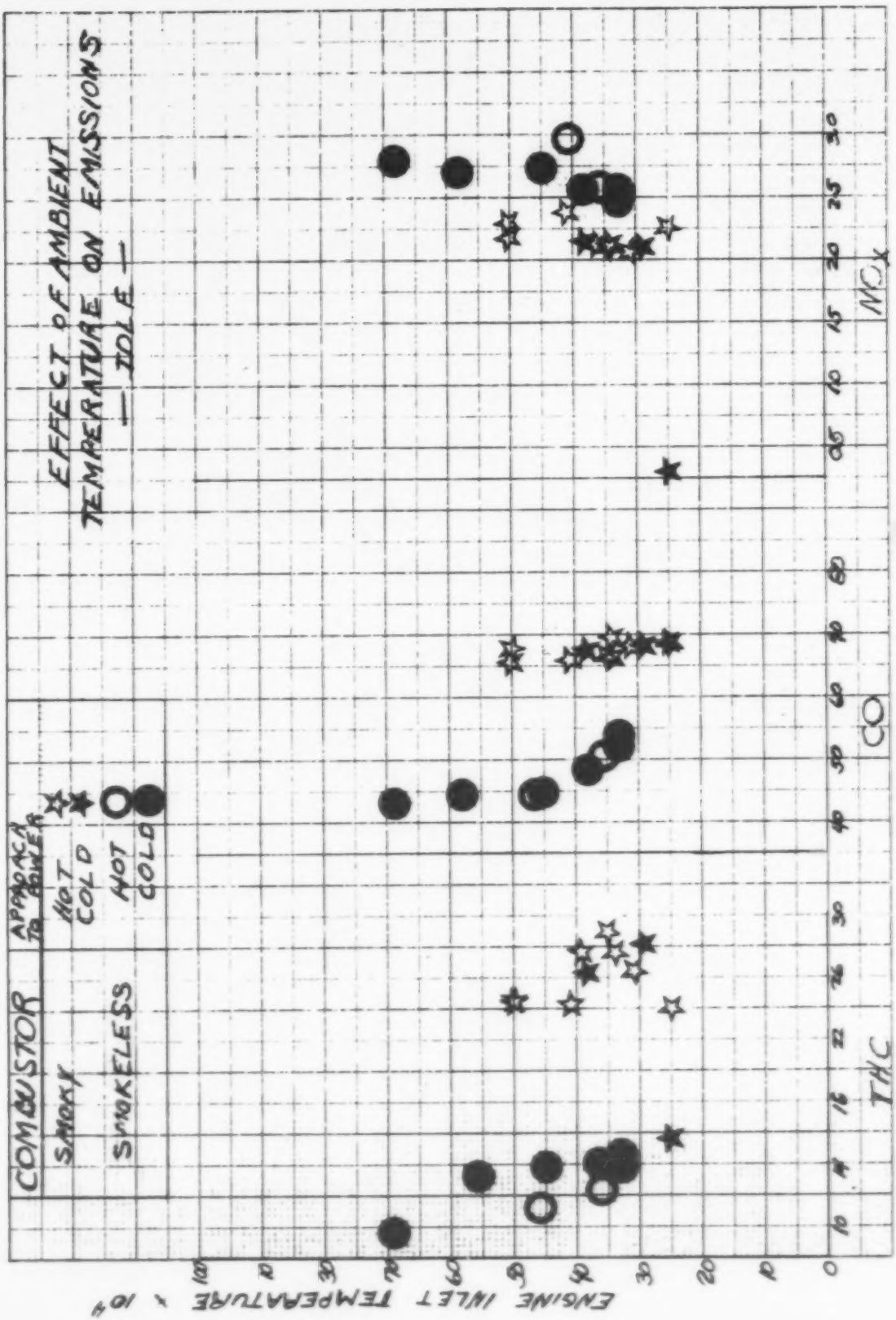

EFFECT OF AMBIENT TEMPERATURE ON EMISSIONS
— IDLE —
COMBUSTOR
SMOKY
SMOKELESS
APPROACH TO BOILER
HOT
COLD
HOT
COLD
ENGINE INLET TEMPERATURE × 10°
EMISSION INDEX
THC
CO
NOx
FUE

FIGURE 8-4

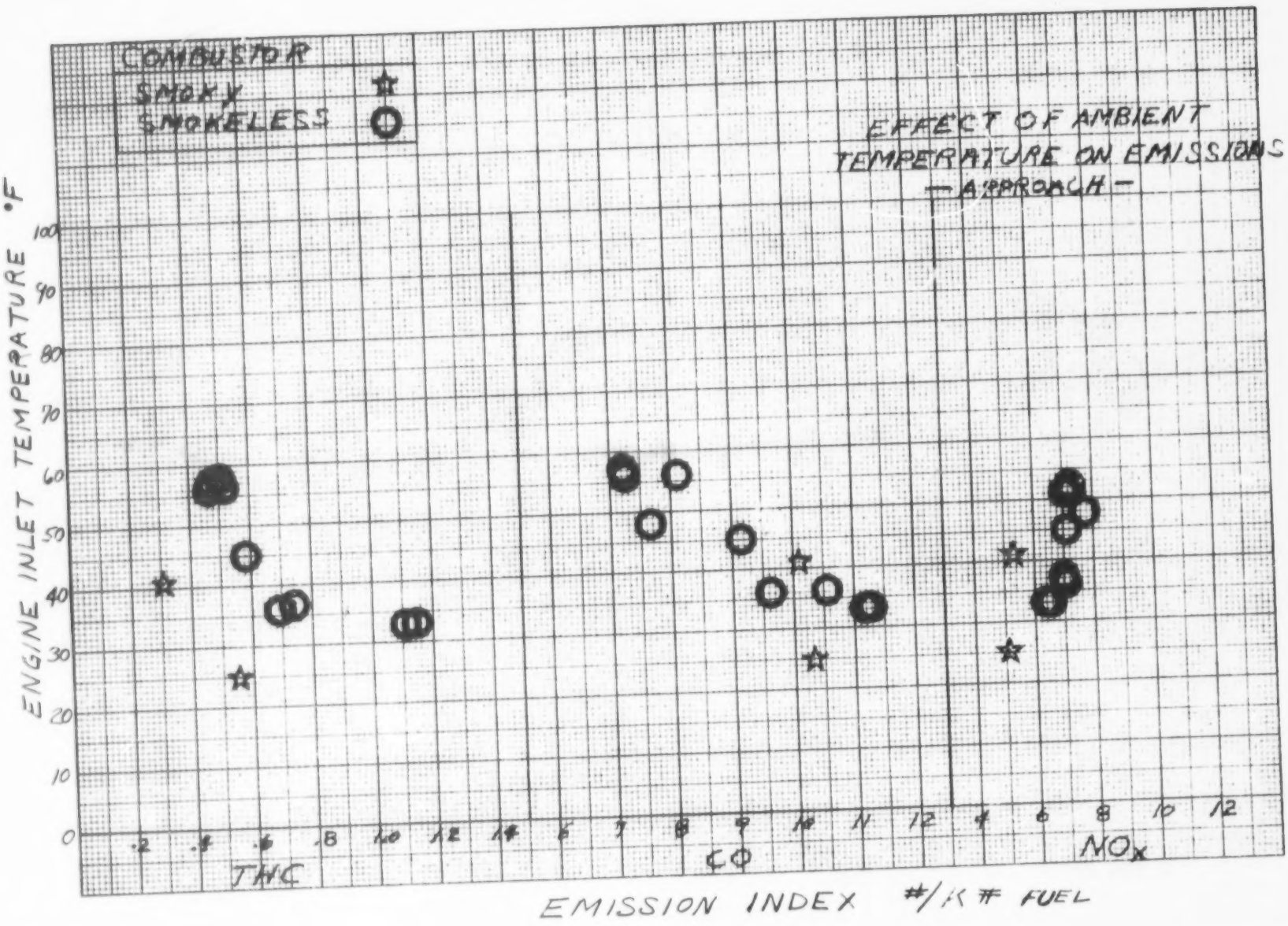
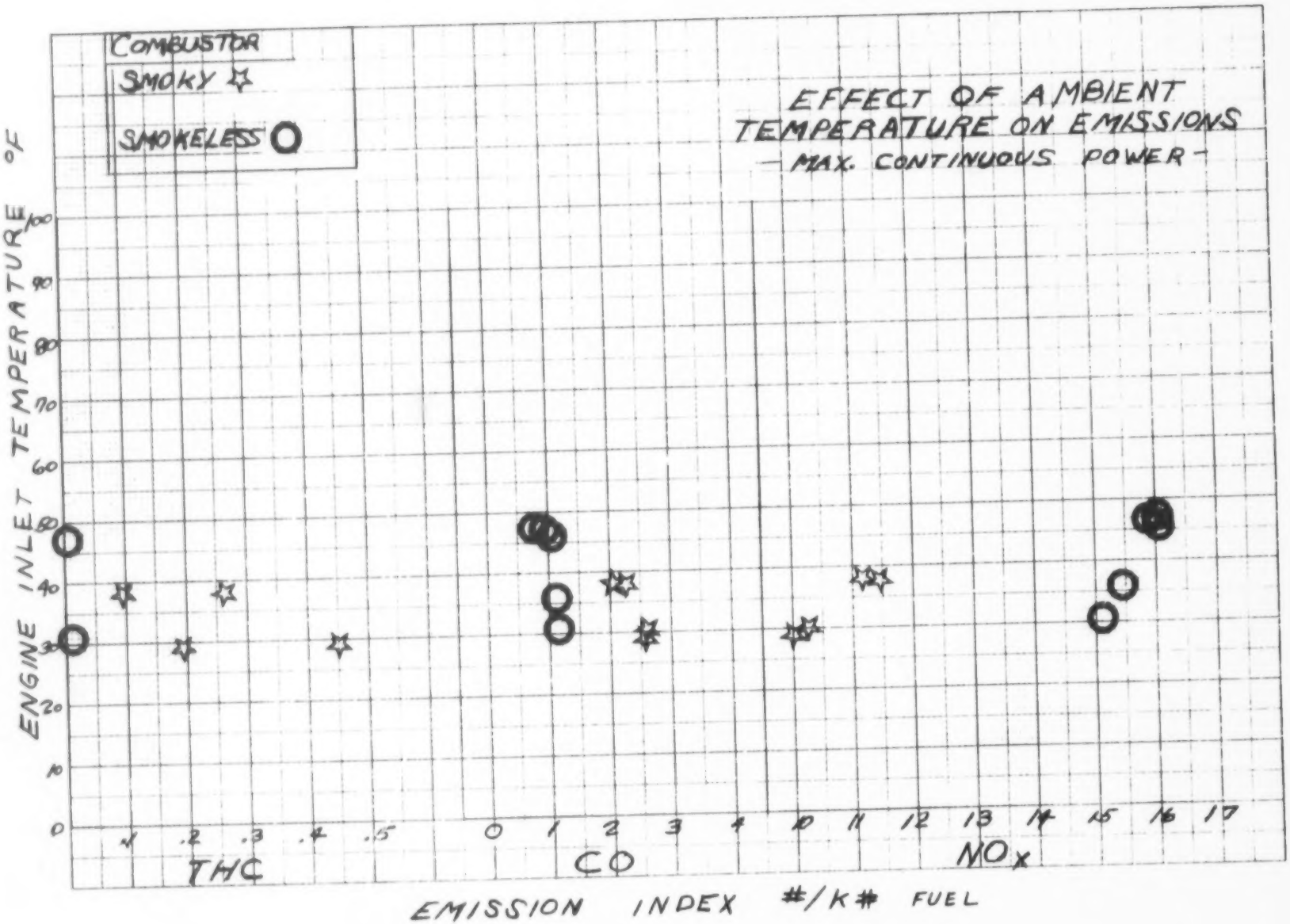

COMBUSTOR
SMOKY
SMOKELESS
EFFECT OF AMBIENT TEMPERATURE ON EMISSIONS
— APPROACH —
ENGINE INLET TEMPERATURE °F
100
90
80
70
60
50
40
30
20
10
0
.2
.4
.6
.8
1.0
1.2
1.4
6
7
8
9
10
11
12
4
6
8
10
12
THC
CO
NOx
EMISSION INDEX #/K # FUEL

FIGURE 8-5


COMBUSTOR
SMOKY
SMOKELESS
EFFECT OF AMBIENT TEMPERATURE ON EMISSIONS
— MAX. CONTINUOUS POWER —
ENGINE INLET TEMPERATURE °F
100
90
80
70
60
50
40
30
20
10
0
.1
.2
.3
.4
.5
0
1
2
3
4
10
11
12
13
14
15
16
17
THC
CO
NOx
EMISSION INDEX #/K# FUEL

9.0 SUMMARY AND CONCLUSIONS

Variability in the measurement of gas turbine emissions is caused by instrument error, calibration gas uncertainty and deficiencies in exhaust gas sampling and handling techniques. Calibration gas uncertainty was found to be the largest contributor to the variability between two measurement systems.

The EPA specified exhaust gas sample handling and conditioning system was found to be adequate and reliable for the handling of gas turbine exhaust samples.

Exhaust sampling methods were studied using both an exhaust mixing technique and a detailed concentration mapping technique using a traversing probe. The mixer technique could not be used at power levels above idle. The detailed concentration maps may require integration with a mass flow profile in order to enable the calculation of true exhaust emission rates.

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APPENDIX A

INSTRUMENT ERROR ANALYSIS

A.1 INTRODUCTION

The error analysis of the individual sub-systems of the turbine system was done by the application of statistical methods to the different analog instruments comprising a sub-system. The analysis essentially gives an "engineering estimate" with a reasonable degree of confidence, for a steady-state accuracy of any proposed analog computing system.

A.1.1 CO Sub-system

The NDIR CO analyzer is essentially a comparitive instrument in that it compares (with some "instrument error") the sample CO level against a reference or standard CO level (which in turn has an error). Thus, the error in a CO sub-system would be that due to the instrument itself, the calibration CO (or no CO) gases and the recorder. Figure A-1 describes the modular structure of the CO sub-system. The notation on the signal arrows denote the signal level and its associated uncertainty; for instance, the signal from the span gas has a level B and an uncertainty in the measurement of that level of ±x or ±y or ±z depending on what point in the error model the measurement is made. The instrument errors which cause this uncertainty are labeled e_1, e_2, etc. P is the signal level at the output of the system. P±f is the recorded response to a sample where ±f is the uncertainty due to the span gases above. P±h is the recorded response to a sample gas where ±h includes both the span gas uncertainty and the recorder and analyzer uncertainty in comparing the sample gas to the span gas.

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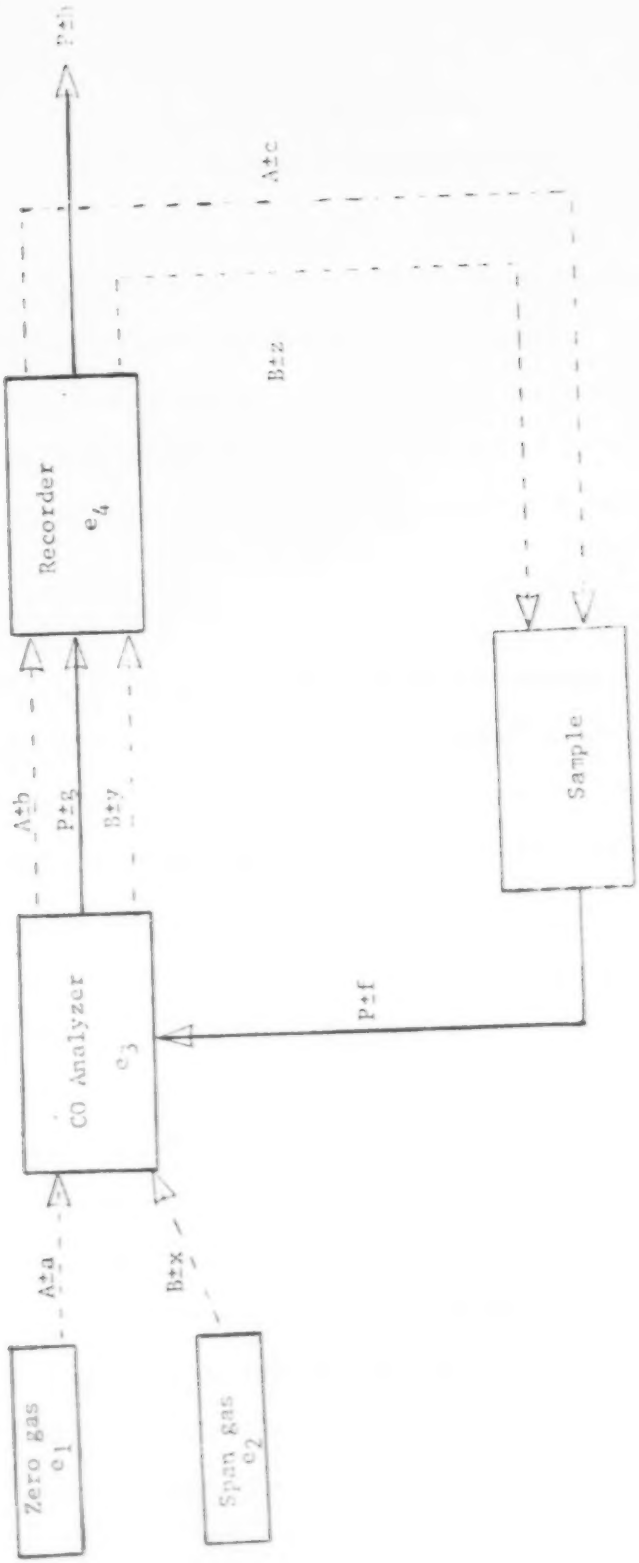

FIGURE A-1 SYSTEM "ERROR FLOW" FOR CO SUB-SYSTEM

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The following errors were determined for the CO sub-system instrumentation:

e_1: ±1%

e_2: ±2% of span value

e_3: ±1% based on repeatability of instrument

e_4: ±0.25% manufacturer's specifications

It should be remembered that the sample gas will be "seen" by the CO analyzer with an error present due to the span and zero gases as well as its own error (repeatability). Referring to Figure A-1.

$a = \pm 1\%$; $b = \pm\sqrt{a^2+e_3^2} = \sqrt{1^2+1^2} = \pm 1.414\%$

$x = \pm 2\%$; $y = \pm\sqrt{x^2+e_3^2} = \sqrt{2^2+1^2} = \pm 2.236\%$

$c = \pm\sqrt{b^2+e_4^2} = \sqrt{2 + 0.25^2} = \pm 1.436\%$

$z = \pm\sqrt{y^2+e_4^2}$

$z = \pm\sqrt{5 + 0.25^2} = \pm 2.25\%$

$f = \pm\sqrt{c^2+z^2} = \sqrt{1.436^2 + 2.25^2} = \pm 2.67\%$

$g = \pm\sqrt{f^2+e_3^2} = \sqrt{2.67^2 + 1^2} = \pm 2.850\%$

$h = \pm\sqrt{g^2+e_4^2} = \sqrt{2.850^2 + 0.25^2} = \pm 2.861\%$

Therefore, the CO sub-system error involved in the system read-out as indicated by the recorder pen is ±2.861%. This is the three standard deviation system error (confidence level of 99.7%) of the output range.

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A.1.2 CO_2 Sub-system

The CO_2 sub-system is entirely analagous to the CO sub-system with the same individual instrument errors. Thus, the steady-state system error as indicated by the recorder pen is also ±2.861%.

A.1.3 NO_x Sub-system

The NO_x system error-flow is essentially the same as the CO and CO_2 sub-system except for the inclusion of a NO_2 - NO converter (see Fig. A-2). The converter has an error associated with it due to its efficiency in converting all the NO_2 to NO. Thus, if the converter is only 99% efficient, there is a possible maximum error of ±1% error associated with it. For the NO_x sub-system the following instrument error values have been determined:

e_1: ±1%

e_2: ±2%

e_3: ±1% manufacturer supplied

e_4: ±0.25% manufacturer supplied

e_5: ±1% assumed

Following in a manner similar to the error analysis for the CO sub-system,

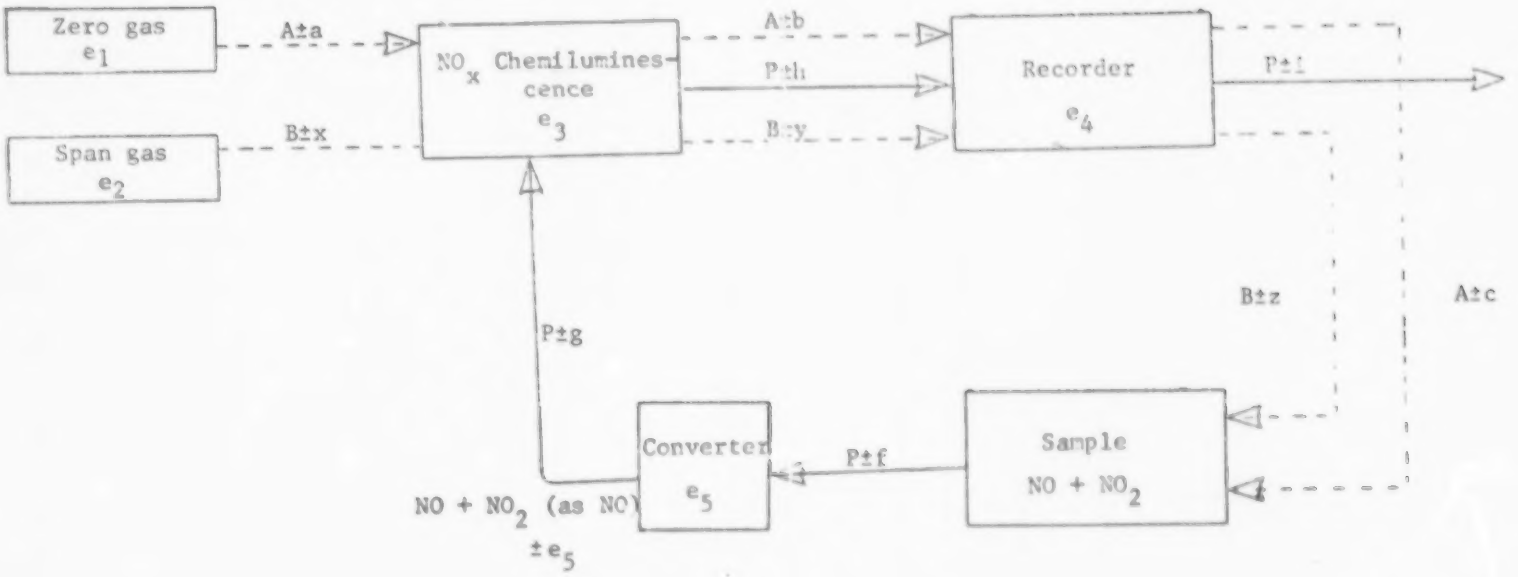
$f = \pm 2.67\%$

$\therefore g = \sqrt{f^2+e_5^2} = \sqrt{2.67^2 + 1^2} = \pm 2.85\%$

$h = \sqrt{g^2+e_3^2} = \sqrt{2.85^2 + 1^2} = \pm 3.02\%$

$i = \sqrt{h^2+e_4^2} = \sqrt{3.02^2 + 0.25^2} = \pm 3.03\%$

FIGURE A-2 SYSTEM "ERROR FLOW" FOR NO_x SUB-SYSTEM



1318 06 0173

If e_5 is assumed = ±2%:

$f = \pm 2.67\%$

$g = \sqrt{2.67^2 + 2^2} = \pm 3.336\%$

$h = \sqrt{3.336^2 + 1^2} = \pm 3.483\%$

$i = \sqrt{3.483^2 + 0.25^2} = \pm 3.492\%$

A.1.4 Total Hydrocarbon Sub-system

The total hydrocarbon (THC) analyzer is also a comparitive instrument, wherein the response and accuracy of the instrument output is dependent on the pressure setting and zero and full scale adjustments from standardized gases. The instrument is also sensitive to errors induced by oxygen in the sample. This "oxygen response" of the instrument is determined prior to its use in any system and if the "oxygen response" is less than 2%, the instrument is considered reliable. The THC analyzer tested for the turbine system was well within this 2% level and hence it is assumed that the "error-flow" of the THC analyzer will pattern itself closely to that of the CO or CO_2 sub-system "error-flow", with the following instrument errors:

e_1: ±1%

e_2: ±2% of span value

e_3: ±1% of full scale

e_4: ±0.25%

Hence, the three standard deviation system error for the total hydrocarbon analyzer is also ±2.861% of the output range.

APPENDIX B

JT8D

Engine Emission Data

Read. No.	Probe Used	Power Condition	Smoke No.	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust - hrs.		
26	NAFEC	Approach	23.1	0.53	8.09	7.32	1.63	24.96	22.59	0.31	4.73	4.28
27	NAFEC	Approach	23.8	0.46	7.26	7.04	1.42	22.29	21.61	0.27	4.22	4.09
28	NAFEC	Cruise	35.1	<0.01	1.38	13.31	0.03	8.56	82.56	0.01	0.78	7.54
29	NAFEC	Cruise	--	<0.01	1.55	13.04	0.03	9.68	81.21	0.01	0.88	7.42
30	NAFEC	Hot Idle	3.7	--	--	--	--	--	--	--	--	--
31	NAFEC	Hot Idle	4.9	--	--	--	--	--	--	--	--	--
32	NAFEC	Take Off	32.3	0.06	0.63	19.74	0.53	5.65	177.50	0.04	0.38	11.99
33	NAFEC	Max.Cont.	33.7	0.01	0.84	15.72	0.10	6.21	115.56	0.01	0.48	8.96
34	NAFEC	Max.Cont.	33.1	0.01	0.97	16.03	<0.03	7.15	117.82	<0.01	0.55	9.06
35	NAFEC		35.1	0.01	1.06	15.31	<0.03	7.40	106.46	<0.01	0.60	8.62
36	NAFEC	Cruise	35.5	0.02	1.38	13.27	0.10	8.65	83.43	0.01	0.78	7.48
37	NAFEC		33.8	0.02	2.23	11.77	0.09	12.10	63.94	0.01	1.25	6.59
38	NAFEC	Landing	32.3	0.03	2.25	11.18	0.17	11.50	57.08	0.02	1.26	6.27
39	NAFEC	Approach	24.1	0.45	7.63	7.74	1.47	25.05	25.41	0.26	4.39	4.46
40	NAFEC	Hot Idle	3.1	--	--	--		--	--	--	--	--
41	NAFEC	Idle Cold	3.1	14.01	48.69	2.54	13.49	46.89	2.45	13.98	48.59	2.54
42	NAFEC	Take Off	32.2	0.01	0.72	17.94	0.85	6.13	152.53	0.06	0.42	10.58
43	NAFEC	Cruise	33.9	0.01	1.66	12.52	0.09	10.22	77.27	0.01	0.92	6.99
44	NAFEC	Approach	23.7	0.74	9.59	7.02	2.21	28.54	20.91	0.40	5.21	3.82
45	NAFEC	Take Off	31.8	0.02	0.67	18.52	0.21	5.65	157.30	0.01	0.39	10.78
46	NAFEC	Idle	6.2									
47	NAFEC	Approach	29.6									
48	NAFEC	Landing	34.2									
49	NAFEC	Cruise	36.8									
50	NAFEC	P.P.	36.0									

Read. No.	Power Condition	Probe Used	Smoke No.	THC	CO	NO_4	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust - hrs.		
1	Idle	NAFEC	--	-	---	-	-	--	-	--	--	-
2	Idle Cold	NAFEC	--	9.59	43.01	2.81	9.53	42.75	2.79	12.71	57.00	3.72
3		NAFEC	--	7.94	39.67	2.95	7.92	39.59	2.94	9.84	49.18	3.65
4		NAFEC	--	7.39	37.49	2.95	7.70	39.06	3.07	9.06	45.95	3.61
5		NAFEC	--	2.54	20.05	3.77	3.59	28.31	5.32	2.42	19.06	3.58
6		NAFEC	--	2.01	17.50	4.05	3.18	27.68	6.40	1.83	15.91	3.68
7	Idle Cold	NAFEC	5.8	11.05	44.00	2.73	10.95	43.60	2.71	14.80	58.92	3.66
8	Approach	NAFEC	26.8	0.47	7.23	7.32	1.41	21.55	21.80	0.28	4.27	4.32
9		NAFEC	30.8	0.13	3.96	8.58	0.50	15.35	33.23	0.07	2.30	4.97
10	Landing	NAFEC	32.6	0.02	2.42	9.96	0.07	11.16	45.83	0.01	1.38	5.66
11	Cruise	NAFEC	37.5	<0.01	1.37	12.82	<0.03	8.00	74.72	0.01	0.77	7.15
12	Idle Cold	NAFEC	4.9	13.83	47.77	2.71	13.62	47.05	2.67	17.92	61.91	3.51
13		NAFEC	7.3	5.07	27.35	3.58	6.86	36.98	4.84	4.97	26.80	3.51
14		NAFEC	22.3	1.54	14.52	5.96	3.59	33.88	13.90	0.92	.64	3.55
15	Approach	NAFEC	26.1	0.58	9.15	7.10	1.73	27.30	21.18	0.34	5.30	4.11
16		NAFEC	31.5	0.15	5.45	8.99	0.56	20.97	34.57	0.08	3.15	5.20
17	Landing	NAFEC	29.8	0.02	2.86	10.45	0.08	13.64	49.88	0.01	1.61	5.90
18		NAFEC	35.7	0.01	2.09	11.36	0.03	11.20	60.99	<0.01	1.16	6.34
19	Cruise	NAFEC	37.5	<0.01	1.53	13.10	<0.03	9.46		0.01	0.86	7.34
20		NAFEC	38.0	0.01	1.12	15.22	0.03	7.77	[illegible]	0.01	0.63	8.56
21	Max.Cont.	NAFEC	38.9	0.01	1.06	16.08	0.03	7.65	115.60	0.01	0.61	9.17
22		NAFEC	38.7	0.01	0.53	17.79	<0.03	4.27	143.21	0.01	0.31	10.30
23	Idle Hot	NAFEC	5.2	11.42	44.04	2.94	11.24	43.34	2.89	12.09	46.60	3.11
24	Idle Cold	NAFEC	3.4	10.89	44.36	2.86	10.90	44.40	2.86	13.62	55.50	3.58
25	Idle Cold	NAFEC	3.0	10.46	43.51	2.76	10.30	42.86	2.72	12.88	53.58	3.40

Read. No.	Power Condition	Probe Used	Smoke No.	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust - hrs.		
51		NAFEC	34.9									
52	Idle	NAFEC										
53	Holding	NAFEC										
54**		NAFEC		1.28	13.71	7.13	3.04	32.44	16.88	0.80	8.54	4.44
55**	Approach	NAFEC		0.66	8.33	8.30	2.00	25.23	25.16	0.40	5.05	5.03
56**	Approach	NAFEC		0.85	9.10	7.17	2.55	27.36	21.56	0.54	5.81	4.58
57***	Idle Hot	NAFEC		13.13	45.57	2.57	13.88	48.17	2.72	18.63	64.66	3.65
58***		NAFEC		7.02	29.34	3.19	9.38	39.23	4.26	8.30	34.72	3.77
59	Idle	NAFEC		13.68	53.46	2.60	13.71	53.57	2.61	14.13	55.23	2.69
60*	Idle	PT_7		20.64	56.67	2.32	20.72	56.90	2.33	19.70	54.09	2.21
61	Idle	NAFEC		14.50	53.88	2.47	14.53	53.99	2.47	13.21	49.08	2.25
62		NAFEC		2.54	17.07	5.56	5.98	40.21	13.09	1.46	9.81	3.19
63*	PP	PT_7		2.40	17.57	5.55	5.66	41.37	13.08	1.38	10.09	3.19
64		NAFEC		2.18	16.74	5.52	5.13	39.43	13.00	1.24	9.55	3.15
65	Approach	NAFEC		1.10	11.22	6.46	3.29	33.54	19.30	0.63	6.39	3.68
66	Approach	PT_7		1.30	12.17	6.42	3.87	36.31	19.15	0.74	6.98	3.68
67	Approach	NAFEC		1.14	11.30	6.58	3.37	33.48	19.51	0.65	6.44	3.75
68		NAFEC		0.50	6.73	8.08	1.89	25.55	30.69	0.28	3.81	4.58
69	PP	PT_7		0.54	7.53	7.98	2.08	28.77	30.49	0.31	4.26	4.52
70		NAFEC		0.37	6.72	7.91	1.43	25.69	30.25	0.21	3.81	4.48
71	Land	NAFEC		0.14	4.13	9.43	0.64	19.43	44.40	0.08	2.34	5.35
72*	Land	PT_7		0.20	4.75	9.64	0.96	22.47	45.65	0.12	2.71	5.50
73	Land	NAFEC		0.11	4.13	9.43	0.53	19.43	44.40	0.06	2.34	5.35
74		NAFEC		0.13	3.12	10.84	0.68	16.13	56.13	0.08	1.79	6.24
75*		PT_7	29.03	0.11	3.60	11.47	0.59	18.82	60.05	0.07	2.08	6.64

* PT_7 Probes ** Five Foot Mixer *** Twenty Foot Mixer

Read. No.	Power Condition	Probe Used	Smoke No.	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust - hrs.		
76	Cruise	NAFEC	31.74	0.03	2.16	12.26	0.16	13.02	73.74	0.02	1.25	7.06
77*	Cruise	PT_7	30.83	0.02	2.34	12.58	0.11	14.09	75.68	0.01	1.35	7.28
78	M.C.P.	NAFEC	33.06	0.01	1.17	15.10	0.10	8.13	104.90	0.01	0.64	8.29
79	M.C.P.	PT_7	32.13	<0.01	1.16	15.23	<0.03	8.11	106.20	<0.01	0.64	8.36
80	Take Off	NAFEC	31.27	0.09	0.77	17.97	0.73	6.26	146.68	0.05	0.44	10.26
81*	Take Off	PT_7	30.90	0.01	0.83	18.68	0.10	6.82	154.20	0.01	0.48	10.78
82	Take Off	NAFEC	28.53	0.01	0.70	18.35	0.10	5.82	151.77	0.01	0.41	10.58
83*	Take Off	PT_7	31.06	<0.01	0.73	18.89	<0.03	6.09	157.90	<0.01	0.42	10.98
84	M.C.P.	NAFEC	31.67	<0.01	1.16	15.49	<0.03	8.06	107.50	<0.01	0.64	8.50
85	M.C.P.	PT_7	31.41	<0.01	1.21	16.11	<0.03	8.46	113.05	<0.01	0.67	8.90
86	Cruise	NAFEC	32.42	<0.01	1.72	12.33	<0.03	10.36	74.36	0.01	0.94	6.77
87	Cruise	PT_7	30.78	<0.01	1.75	13.45	<0.03	10.66	81.84	<0.01	0.97	7.45
88	Landing	NAFEC	29.03	0.01	3.25	10.38	0.05	15.30	48.89	0.01	1.78	5.68
89	Landing	PT_7	26.86	0.12	3.57	10.78	0.56	16.81	50.76	0.07	1.95	5.90
90	Approach	NAFEC	20.31	0.69	10.53	7.09	2.03	31.18	21.10	0.39	5.97	4.04
91	Approach	PT_7	20.48	0.86	11.53	6.97	2.51	33.60	2 .31	0.49	6.49	3.92
92	Holding	NAFEC	--	6.33	32.92	3.35	8.12	42.20	4.29	6.01	31.26	3.18
93	Holding	PT_7	--	6.92	35.27	3.47	8.87	45.21	4.45	6.57	33.49	3.30
94	Idle	NAFEC	--	12.41	50.83	2.59	11.86	48.59	2.48	14.12	57.85	2.95
95	Idle	PT_7	--	13.97	54.06	2.68	13.36	51.68	2.56	15.90	61.52	3.05
96	Idle	NAFEC	43.56	15.60	63.36	1.83	16.01	65.01	1.88	17.80	72.31	2.09
97	Holding	NAFEC	48.73	11.78	47.79	2.05	15.11	61.31	2.63	11.34	46.00	1.97
98	P.P.	NAFEC	64.23	1.12	15.13	4.41	2.65	35.65	10.39	.68	9.19	2.68
99	Approach	NAFEC	68.71	.55	10.30	5.18	1.61	30.03	15.10	.32	6.01	3.02
100	Idle	NAFEC	--	24.18	65.59	2.26	24.81	67.30	2.32	27.29	74.03	2.55

Read. No.	Power Condition	Probe Used	Smoke No.	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust - hrs.		
101	Idle	NAFEC	--	26.16	68.17	2.08	27.47	71.58	2.18	32.01	83.42	2.55
102	P.P.	NAFEC	71.48	.76	7.01	6.19	2.87	26.33	23.25	.44	4.04	3.57
103	Landing	NAFEC	74.49	.31	4.87	7.48	1.49	23.06	35.43	..18	2.80	4.30
104	P.P.	NAFEC	73.75	.21	4.01	7.95	1.11	20.96	41.55	.12	2.29	4.55
105	Cruise	NAFFC	75.23	.09	3.29	9.04	.55	19.88	54.63	.05	1.89	5.20
106	Max.Cont.	NAFEC	76.70	.19	2.68	10.01	1.35	18.76	70.06	.11	1.55	5.78
107	Take Off	NAFEC	83.29	18	1.85	12.61	1.60	15.96	108.79	.11	1.11	7.57
108	Take Off	NAFEC	78.78	.29	1.97	12.32	2.54	17.00	106.28	.17	1.18	7.41
109	Max. Cont.	NAFEC	77.61	.45	2.64	10.26	3.18	18.53	72.00	.26	1.53	5.94
110	Idle	NAFEC	45.06	26.35	--	2.15	25.80	--	2.10	29.69	--	2.42
111	Take Off	NAFEC	78.11	.61	1.89	12.27	5.37	16.44	106.71	.37	1.14	7.39
112	Max. Cont.	NAFEC	80.50	.26	2.05	11.47	2.11	16.36	91.52	.15	1.21	6.78
113	Max. Cont.	NAFEC	77.41	.09	2.27	11.14	.73	17.25	84.68	.05	1.33	6.52
114	Cruise	NAFEC	76.70	.06	3.07	9.03	.39	9.62	55.37	.03	.90	5.22
115	Landing	NAFEC	75.90	.14	4.44	7.46	.71	21.53	36.18	.08	2.60	4.37
116	Approach	NAFEC	69.36	.30	10.11	5.30	9.15	30.42	15.95	1.83	6.08	3.19
117	Holding	NAFEC	51.50	8.92	46.15	2.81	11.64	60.23	3.67	9.04	46.76	2.85
118	Idle	NAFEC	48.35	24.25	65.95	2.37	25.44	69.18	2.49	29.65	80.63	2.90
119	Idle	Traverse	--	19.50	63.70	2.56	19.15	62.55	2.51	22.61	73.85	2.97
120	Approach	Traverse	--	.34	8.44	5.66	1.03	25.12	16.84	.20	4.82	3.23
121	Approach	Traverse	--	.34	8.44	5.66	1.03	25.12	16.84	.20	4.82	3.23
122	Max.Cont.	Traverse	--	.10	2.80	11.02	.74	19.36	76.21	.05	1.55	6.09
123	Max.Cont.	Traverse	--	.10	2.80	11.02	.74	19.36	76.21	.05	1.55	6.09
124	Idle	Traverse	--	18.70	62.90	2.52	18.85	63.40	2.54	21.97	73.90	2.96
125	Holding	Traverse	--	4.60	38.40	3.05	6.20	51.72	44.12	4.41	36.84	2.93

Read. No.	Power Condition	Probe Used	Smoke No.	THC	CO	NO_x	THC	CO	NO_x	THC	CO	NO_x
				pounds/K pounds fuel			pounds/hour			pounds/K pound thrust-hrs.		
126	Take Off	NAFEC	--	--	--	--	--	--	--	--	--	--
127	Take Off	NAFEC	--	--	--	--	--	--	--	--	--	--
128	Take Off	NAFEC	--	--	--	--	--	--	--	--	--	--
129	Take Off	NAFEC	--	--	--	--	--	--	--	--	--	--
130	Take Off	Traverse	--	--	--	--	--	--	--	--	--	--
131	Take Off	Traverse	--	--	--	--	--	--	--	--	--	--
132	Take Off	Traverse	--	--	--	--	--	--	--	--	--	--
133	Approach	Traverse	--	--	--	--	--	--	--	--	--	--
134	Idle	Traverse	--	--	--	--	--	--	--	--	--	--
135	Idle	Traverse	--	--	--	--	--	--	--	--	--	--
136	Idle	Traverse	--	--	--	--	--	--	--	--	--	--

For Emissions Data obtained during Reading Numbers 137-155, see Table 6-2, Probe Comparison Data

APPENDIX C

JT8D

Engine Operating Data

Read NO.	Power Setting	Thrust (pounds)	EPR	Fuel Flow lbs./hr	W_A Air Flow lbs/sec	N_1 rpm	N_2 rpm	PT_7 (in.Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure (in.Hg)
1	Idle	745	1.041	998	22	2468	6433	1.25	650	55	30.56
2	Idle	750	1.042	994	17	2516	6528	1.25	685	70	29.79
3	--	805	1.042	998	24	2591	6636	1.25	680	67	30.06
4	--	850	1.042	1042	15	2654	6730	1.25	680	67	30.03
5	--	1485	1.076	1412	59	3407	7715	2.25	700	67	30.02
6	--	1740	1.093	1582	66	3646	8000	2.75	700	65	30.02
7	Idle	740	--	991	4	2486	6451	1.25	650	55	29.99
8	Approach	5050	1.297	2980	196	5577	9568	10.50	300	55	29.99
9	--	6680	1.550	3872	213	6172	10001	22.00	330	57	29.97
10	Landing	8100	1.503	4602	247	6612	10295	22.00	350	55	29.97
11	Cruise	10450	1.671	5828	272	7107	10670	22.00	--	55	29.97
12	Idle	760	1.041	985	69	2434	6337	1.25	660	43	30.46
13	--	1380	1.073	1352	110	3207	7398	2.25	680	43	30.46
14	--	3920	1.222	2334	183	4990	9063	6.75	610	43	30.46
15	Approach	5150	1.304	2984	209	5556	8480	9.25	650	45	30.46
16	--	6650	1.412	3846	243	6119	9334	12.50	715	45	30.46
17	Landing	8460	1.544	4773	262	6630	10231	16.50	760	45	30.46
18	--	9620	1.629	5367	277	6865	10415	19.00	800	45	30.44
19	Cruise	11000	1.729	6164	288	7162	10617	22.00	840	45	30.44
20	--	12350	1.845	6945	301	7442	10805	25.50	875	45	30.44
21	Max.Cont.	12610	1.879	7189	160	7523	10860	26.50	880	45	30.44
22	--	1391	1.979	8051	313	7815	11039	29.50	920	45	30.44
23	Idle Hot	930	1.041	984	90	2468	6371	1.25	650	45	30.44
24	Idle	800	1.041	1001	81	2509	6475	1.25	690	55	30.09
25	Idle	800	1.041	985	80	2507	6474	1.25	690	55	30.09

Read No.	Power Setting	Thrust (pounds)	EPR	Fuel Flow lbs/hr.	W_A Air Flow lbs/sec.	N_1 ppm	N_2 ppm	PT_7 (in. Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure (in. Hg)
26	Approach	5280	1.308	3086	213	5673	9628	9.25	685	55	30.14
27	Approach	5280	1.308	3069	212	5676	9634	9.25	685	55	30.14
28	Cruise	10950	1.744	6201	288	7232	10720	22.25	660	55	30.14
29	Cruise	10950	1.744	6230	--	---	--	--	--	--	--
30	Idle Hot	760	1.033	961	85	2448	6374	1.00	690	55	30.14
31	Idle	775	1.033	98[illegible]	74	2482	6423	1.00	680	45	30.31
32	Take Off	14800	2.084	8994	321	8117	11205	32.50	980	47	30.31
33	Max.Cont.	12900	1.899	7352	307	7600	10922	27.00	900	47	30.31
34	Max.Cont.	13000	1.892	7352	306	7588	10917	26.77	000	47	30.30
35	--	12350	1.849	6953	301	7457	10829	25.50	000	45	30.30
36	Cruise	11150	1.707	6286	289	7200	10666	21.25	000	47	30.30
37	--	9700	1.616	5431	271	6892	10453	18.50	000	47	30.28
38	Landing	9100	1.574	5107	264	6784	10361	17.25	000	47	30.28
39	Approach	5700	1.323	3285	215	5776	9667	9.75	000	4[illegible]	30.28
40	Idle Hot	850	1.025	985	80	2490	6427	0.75	000	48	30.28
41	Idle	965	1.042	963	76	2465	6374	1.25	660	40	29.82
42	Take Off	14422	2.046	8500	321	7950	11081	31.00	940	40	29.85
43	Cruise	11055	1.714	6171	293	7965	10564	22.00	830	40	29.85
44	Approach	5477	1.302	2977	211	5566	9470	9.00	650	40	29.87
45	Take Off	14593	2.064	8494	322	7994	11118	31.50	940	40	29.87
46	Idle	1015	1.042	8494	85	2511	6438	1.25	645	30	30.07
47	Approach	5399	1.300	2942	210	5538	9412	9.00	640	30	30.07
48	Landing	8885	1.554	4763	264	6595	10160	16.50	750	30	29.98
49	Cruise	11137	1.732	5975	286	7085	10517	21.75	810	30	29.98
50	P.P.	12731	1.876	6938	303	7418	10721	26.00	850	30	29.98

Read No.	Power Setting	Thrust (pounds)	EPR	Fuel Flow lbs/hr.	W_A Air Flow lbs/sec.	N_1 ppm	N_2 ppm	PT_7 (in-Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure
51	Take Off	8592	2.038	8244	319	7888	11020	30.80	915	30	29.98
52	Idle	996	1.033	983	82	2638	6620	1.00	650	42	30.16
53	Holding	1375	1.051	1356	114	3306	7489	1.55	660	42	30.16
54	P.P.	3800	1.188	2367	173	5200	7174	5.60	628	53	30.04
55	Approach	5000	1.281	3030	155	5760	9600	8.30	665	53	30.04
56	Approach	4710	1.255	3006	---	5810	9590	7.60	557	50	29.95
57	Idle	745	1.028	1057	94	2657	6677	0.85	660	50	29.84
58	Holding	1130	1.044	1337	114	3220	7395	1.30	670	48	29.84
59	Idle	970	1.040	1002	80	2438	6315	1.20	650	33	30.15
60	Idle	1052	1.040	1004	80	2430	6304	1.20	650	33	30.15
61	Idle	1100	1.040	1002	77	2434	6307	1.20	650	33	30.15
62	P.P.	4100	1.208	2355	178	4856	8891	6.25	595	32	30.15
63	P.P	4100	1.208	2355	179	4868	8906	6.25	610	32	30.15
64	P.P.	4130	1.208	2355	179	4866	8900	6.25	610	32	30.15
65	Approach	5250	1.285	2988	204	5414	9317	8.55	650	29	30.15
66	Approach	5200	1.285	2984	204	5292	9305	8.55	640	29	30.15
67	Approach	5200	1.282	2964	203	5391	9303	8.45	640	30	30.15
68	P.P.	6700	1.394	3796	231	5990	9730	11.80	685	30	30.15
69	P.P.	6750	1.395	3819	232	5999	9736	11.85	690	30	30.15
70	P.P.	6750	1.397	3823	232	6006	9736	11.90	690	28	30.15
71	Landing	8300	1.512	4709	257	6466	10057	15.35	730	28	30.15
72	Landing	8300	1.512	4733	257	6467	10055	15.35	725	30	30.15
73	Landing	8300	1.512	4709	255	646	10053	15.35	730	30	30.19
74	P.P.	9000	1.577	5176	260	6689	10215	17.20	750	26	30.01
75	P.P.	9050	1.577	5234	264	6703	10232	17.20	760	30	30.01

Read. No.	Power Setting	Thrust (pounds)	EPR	Fuel Flow lbs./hr.	W_A Air Flow lbs/sec.	N_1 ppm	N_2 ppm	PT_7 (in.Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure
76	Cruise	10450	1.680	6015	287	6960	10427	20.25	800	30	30.01
77	Cruise	10400	1.681	6015	280	6976	10438	20.25	800	30	30.01
78	Max.Cont.	12650	1.885	6948	303	7467	10756	26.30	865	31	30.01
79	Max.Cont.	12700	1.885	6971	305	7490	10773	26.30	870	31	30.01
80	Take Off	14300	2.048	8161	319	7908	11049	31.00	930	30	29.93
81	Take Off	14300	2.047	8254	318	7907	11034	31.00	925	32	29.93
82	Take Off	14350	2.049	8270	319	7962	11034	31.00	930	35	29.88
83	Take Off	14380	2.049	8358	319	7948	11080	31.00	940	32	29.88
84	Max.Cont.	12650	1.887	6940	304	7503	10802	26.25	875	34	29.88
85	Max.Cont.	12700	1.888	7018	303	7518	10808	26.25	875	32	29.88
86	Cruise	10990	1.738	6031	287	7122	10556	21.85	820	32	29.88
87	Cruise	10990	1.738	6085	288	7137	10568	21.85	830	33	29.88
88	Landing	8600	1.550	4709	257	6611	10187	16.30	750	33	29.88
89	Landing	8600	1.551	4709	256	6613	10179	16.30	750	32	29.88
90	Approach	5220	1.303	2961	218	5550	9442	9.10	645	32	29.85
91	Approach	5180	1.303	2915	217	5523	9420	9.10	645	32	29.85
92	Holding	1350	1.070	1282	114	3148	7299	2.10	665	33	29.85
93	Holding	1350	1.070	1282	113	3140	7289	2.10	665	35	29.85
94	Idle	840	1.059	956	92	2513	6433	1.75	650	35	29.85
95	Idle	840	1.059	956	91	2497	6419	1.75	645	35	29.85
96	Idle	899	1.043	1026	N/A	2476	6375	1.30	650	25	30.17
97	Holding	1333	1.065	1283	N/A	3020	7092	1.95	640	25	30.17
98	P.P.	3878	1.209	2356	N/A	4845	8846	6.30	610	25	30.17
99	Approach	5000	1.281	2916	N/A	5362	9247	8.45	625	25	30.17
100	Idle	909	1.043	1026	N/A	2527	6432	1.30	645	25	30.17

Read. No.	Power Setting	Thrust (pounds)	FPR	Fuel Flow lbs./hr.	W_A Air Flow lbs./sec.	N_1 rpm	N_2 rpm	PT_7 (in.Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure
101	Idle	858	1.043	1050	N/A	2498	6405	1.30	655	28	30.10
102	P.P.	6514	1.397	3756	N/A	5957	9686	11.70	680	27	30.10
103	Landing	8232	1.518	4736	N/A	6483	10051	15.50	730	27	30.10
104	P.P.	9140	1.585	5226	N/A	6680	10208	17.50	760	27	30.10
105	Cruise	10504	1.690	6043	N/A	6963	10419	20.60	805	30	30.10
106	Max.Cont.	12120	1.833	6999	N/A	7320	10646	24.90	8'	28	30.18
107	Take Off	14362	2.025	8627	N/A	7835	10974	30.60	910	30	30.18
108	Take Off	14342	2.022	8627	N/A	7833	10974	30.50	910	30	30.18
109	Max.Cont.	12120	1.819	7018	N/A	7310	10644	24.50	835	28	30.18
110	Idle	869	1.041	979	N/A	2510	6454	1.25	680	37	30.38
111	Take Off	14443	2.012	8697	N/A	7866	11024	30.50	930	35	30.39
112	Max.Cont.	13484	1.934	7979	N/A	7627	10871	28.10	900	34	30.39
113	Max.Cont.	12978	1.887	7601	N/A	7495	10794	26.70	880	34	30.39
114	Cruise	10605	1.690	6132	N/A	6985	10470	20.80	820	35	30.39
115	Landing	8282	1.513	4850	N/A	6508	10112	15.50	745	35	30.41
116	Approach	5000	1.284	3009	N/A	5407	9339	8.60	650	35	30.41
117	Holding	1288	1.064	1305	N/A	3034	7148	1.95	660	35	30.41
118	Idle	858	1.041	1049	N/A	2506	6435	1.25	670	35	30.41
119	Idle[1]	847	1.041	982	N/A	2509	6485	1.26	648	42	30.23
120	Approach[1]	5207	1.291	2991	N/A	5507	9435	8.77	621	36	30.16
121	Approach[1]	5213	1.302	1961	212.0	5604	9580	8.94	652	54	29.63
122	Max.Cont.	12519	1.873	6916	303.8	7440	10743	25.62	824	29	29.68
123	Max.Cont.	12519	1.873	6916	303.8	7440	10743	25.62	824	29	29.68
124	Idle	858	1.042	1008	81.5	2540	6514	1.25	663	46	30.13
125	Holding	1404	1.070	1347	110.0	3256	7475	2.11	661	47	30.07

1) Traverse

Read. No.	Power Setting	Thrust (pounds)	EPR	Fuel Flow lbs./hr.	W_A Air Flow lbs./sec.	N_1 ppm	N_2 ppm	PT_7 (in.Hg)	TT_7 (^oF)	TT_2 (^oF)	Barometric Pressure
126	Take Off[1]	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
127	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
128	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
129	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
130	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7045[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
131	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
132	Take Off	14306[2]	2.019[2]	8294[2]	318[2]	7945[2]	11167[2]	30.27[2]	929[2]	46[2]	30.00[2]
133	Approach	4646	1.269	2671	200	5327	9271	7.95	600	31	29.72
134	Idle	808	1.040	975	83	2468	6384	1.20	640	32	29.72
135	Idle	859	1.043	998	85	2619	6575	1.27	630	38	29.67
136	Idle	808	1.040	998	81	2532	6499	1.20	655	45	30.23
137	Idle	808	1.040	998	81	2519	6480	1.20	655	45	30.23
138	Idle	808	1.040	1003	81	2537	6512	1.20	660	48	30.23
139	Idle	808	1.040	1021	81	2547	6524	1.20	660	47	30.23
140	Idle	758	1.040	998	81	2339	6513	1.20	660	44	30.20
141	Idle	783	1.040	998	81	2530	6483	1.20	655	44	30.23
142	Idle	808	1.041	998	83	2523	6454	1.25	630	33	30.25
143	Idle	808	1.041	998	81	2526	6458	1.25	630	33	30.25
144	Idle	859	1.040	998	85	2522	6454	1.25	630	34	30.24
145	Idle	808	1.041	1021	83	2515	6439	1.25	630	34	30.24
146	Idle	782	1.040	998	83	2471	6373	1.20	630	32	30.19
147	Idle	707	1.040	998	81	2487	6403	1.20	630	33	30.19
148	Idle	798	1.040	975	83	2477	6379	1.20	620	33	30.20
149	Idle	798	1.040	998	83	2487	6398	1.20	625	34	30.20
150	Idle	828	1.040	1021	83	2522	6453	1.25	630	33	30.33
151	Idle	828	1.040	998	81	2509	6431	1.20	650	43	30.32
152	Idle	828	1.040	998	81	2497	6440	1.25	650	42	30.32
153	Idle	808	1.041	998	81	2462	6377	1.20	650	42	30.30
154	Idle	848	1.043	998	81	2485	6412	1.25	650	42	30.30
155	Idle	848	1.043	975	81	2465	6384	1.25	650	41	30.30

1. Traverse
2. Average for traverse made during reading numbers 126-132.

END